WADD TECHNICAL REPORT 60-438

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ELEVATED TEMPERATURE DYNAMIC ELASTIC MODULI OF VARIOUS METALLIC MATERIALS

W. H. HILL
K. D. SHIMMIN

MATERIALS CENTRAL

MARCH 1961

WRIGHT AIR DEVELOPMENT DIVISION

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ELEVATED TEMPERATURE DYNAMIC ELASTIC MODULI OF VARIOUS METALLIC MATERIALS, by W. H. Hill and K. D. Shimmin, March 1961. 75 p. incl. figs. and tables. (Project 7351; Task 73521) (WADD TR 60-438) Unclassified report.

The dynamic elastic moduli of 40 metals and alloys of engineering interest have been determined at room and elevated temperatures. Modulus determinations were based upon a relation between the speed of sound in a material and its elastic modulus. A specimen of the material was excited electrostatically and its

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resonant frequency determined. Knowing the geometry of the specimen, the dynamic elastic modulus was calculated.

Room temperature comparisons of dynamic with static moduli were made in most instances using material from the same bar.

The results of dynamic elastic modulus determinations are graphically presented.

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MARCH 1961

PROJECT No. 7351
TASK No. 73521

WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by the Creep and Dynamics Section, Metals and Ceramics Laboratory, Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division. The program was conducted under Project No. 7351, "Metallic Materials," Task No. 73521, "Behavior of Metals" as an internal research effort. This work was performed by W. H. Hill and K. D. Shimmin during the period from August 1959 to July 1960.

The authors wish to acknowledge the contribution of Mr. E. H. Beutel in the unique design and fabrication of the test fixture which made this program possible.

ABSTRACT

The dynamic elastic moduli of 40 metals and alloys of engineering interest have been determined at room and elevated temperatures. Modulus determinations were based upon a relation between the speed of sound in a material and its elastic modulus. A specimen of the material was excited electrostatically and its resonant frequency determined. Knowing the geometry of the specimen, the dynamic elastic modulus was calculated.

Room temperature comparisons of dynamic with static moduli were made in most instances using material from the same bar.

The results of dynamic elastic modulus determinations are graphically presented.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. J. Trapp

W. J. TRAPP
Chief, Strength and Dynamics Branch
Metals and Ceramics Laboratory
Materials Central

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INTRODUCTION

In the design of load-carrying members subjected to high temperature as well as stress, it is imperative that Young's modulus be known so that deflections can be calculated for any combination of stress and temperature. This property is conventionally determined from the static stress-strain plots of one or several samples tested at each temperature. This widely accepted method has several disadvantages which are discussed more completely later in the report. The principal disadvantage is the large number of carefully prepared specimens needed to establish the temperature dependence of modulus for a given material.

Another approach to determination of the elastic modulus (Young's modulus) exists because there is a relationship between the speed of sound in a material and its elastic modulus. Since the speed of sound in a material is manifested in its resonant frequency, it becomes necessary only to determine that property of a material at elevated temperatures to determine the elevated temperature modulus. This determination is obtained nondestructively, thus permitting a large number of determinations at various temperatures from the same sample.

TEST PROGRAM

The program reported here has been conducted for the purpose of evaluating the elevated temperature dynamic modulus of a wide variety of metals and alloys. The special equipment was designed and fabricated for determining the longitudinal resonance of a test sample. In order to provide a comparison of dynamically and statically determined moduli, conventional static modulus tests were performed at room temperature on several materials.

MATERIALS

The materials considered as representative of those of general interest for elevated temperature structural applications were: Aluminum, beryllium, copper, titanium, iron, cobalt, nickel and refractory alloys. In addition, several pure metals were investigated to provide an indication of the effect upon modulus of alloy additions. Alloys of engineering interest were tested in the condition of heat-treatment considered to be of widest application. Many materials, mostly steels, were tested in both annealed and heat-treated conditions, and the response comparisons are shown graphically. The heat treatment, composition and other pertinent data for each material are given on the data sheet for that material.

Manuscript released by the authors 15 July 1960 for publication as a WADD Technical Report.

The following is a complete list of the materials tested and is arranged by alloy group:

Aluminum and Aluminum Alloys

High purity aluminum (As Cold Rolled)

2024-T4

7075-T6

Beryllium

Commercial purity beryllium, (powder metallurgy)

Copper Alloys

Beryllium copper (Conditions A and AT)

Titanium and Titanium Alloys

Ti-6Al-4V (Annealed)

Iodide titanium (As Grown)

Ti-75A (Annealed)

B-120VCA (Annealed)

Steels

SAE 1020 (As Hot Rolled)

SAE 4130 (Heat Treated)

SAE 4340 (Heat Treated)

La Belle HT (Annealed and Heat Treated)

Peerless 56 (Annealed and Heat Treated)

Vascojet 1000 (Heat Treated)

AISI Type 410 (Heat Treated)

AM 350 (Heat Treated, SCT 850F)

Timken 16-25-6 (Annealed)

17-7 PH (Conditions A and TH 1050)

PH 15-7 Mo (Conditions A and TH 1050)

A-286 (Heat Treated)

Low Expansion Alloys

Invar

Cobalt Alloys

S-816 (Two Conditions of Heat Treatment)

Nickel and Nickel Alloys

Electrolytic Nickel (As Deposited)

Inconel (Annealed)

Inconel W (Annealed)

Inconel X (Heat Treated)

Hastelloy B (Heat Treated)

Nimonic 90 (Heat Treated)

Waspaloy (Heat Treated)

M 252 (Heat Treated)

René 41 (Heat Treated)

Udimet 500 (Heat Treated)

Udimet 700 (Wrought and Cast, both Heat Treated)

Inconel 700 (Heat Treated)

Inconel 713C (As Investment Cast)

Refractory Metals and Alloys

Commercial Purity Molybdenum

Vanadium (Aluminothermic and Calcium-Reduced)

Commercial Purity Tungsten

F-80 (As Cold Drawn)

BACKGROUND AND THEORY

The program to determine dynamic modulus of elasticity of metals and alloys had two objectives: the first objective was to develop the equipment and techniques to determine modulus values on small specimens at elevated temperatures, and the second objective was to obtain elevated temperature modulus data on a group of metals and alloys under conditions of limited exposure time to temperature.

The requirement for small specimen size was based on the need to evaluate modulus of elasticity of samples where only limited amounts of material were available, such as in the case of experimental alloys and specimens taken from parts such as turbine blades. It was also desired to keep the specimen configuration simple in the case of materials which were difficult to machine.

After review of the various available means for modulus determinations, the decision was made to use the dynamic method utilizing longitudinal vibration of a rod with electrostatic excitation. In the longitudinal vibration of a rod, if one end of the rod is displaced back and forth, the displacement propagates down the length of the rod with a velocity equal to $\sqrt{E/\rho}$, where E is the modulus of elasticity, and ρ is the rod density. The displacement wave is reflected from the non-driven end of the specimen and interacts with the forward propagating wave to give constructive or destructive interference. If the length of the specimen is some multiple of a half-wave length associated with the driving frequency, the interference is constructive and the conditions for resonant vibration are met. The resonant frequency is that given by:

$$f_n = \frac{V}{\lambda} = \frac{n}{2L}\sqrt{\frac{E}{\rho}} \qquad (1)$$

where:

V	=	Velocity of propagation
λ	=	Wave length
n	=	An integer associated with the number of half-wave lengths in the rod or the mode of vibration
L	=	Length of the rod

This equation is rearranged to give the relationship between modulus and the other terms as follows:

$$E = \frac{4L^2}{n^2} \rho f_n^2 \tag{2}$$

and is approximately correct as long as the ratio of length to cross sectional dimensions of the rod is large (10 to 1 or greater). Otherwise a correction for the effect of Poisson's ratio must be made. The relation also must be corrected in those cases where large internal friction (damping) is encountered. The corrections for Poisson's ratio and for damping are considered in greater detail in the section on accuracy.

Using the relationship between modulus and resonant frequency given in equation (2) it is possible to obtain the modulus by exciting a rod longitudinally by means of a variable frequency drive and determining the resonant frequency by observing the maximum in amplitude of vibration. Three means of exciting the rod are available: electromagnetic, electrostatic, or piezoelectric excitation. In this program electrostatic excitation and vibration pickup was chosen. The other methods have limitations such as: requirement for ferromagnetic materials or adaptors (electromagnetic) and requirement for cementing crystals or adaptor rods to specimens (piezoelectric).

Static modulus of elasticity determinations were conducted at room temperature on a majority of the test materials for comparison with the room temperature dynamic modulus results. Part of the difference between static and dynamic results may be attributed to experimental error. However, there are some differences between static and dynamic results which can be predicted theoretically. Among these is a thermodynamic difference. When a tensile or compressive stress is applied to a rod there is a volume change. When the volume decreases, heat is produced in the rod and when the volume increases heat is absorbed. In static tests there is sufficient time available for exchange of heat with surroundings, so that a static test may be considered an isothermal test. However, in dynamic tests there is insufficient time for exchange of heat with the surrounding environment, so that dynamic tests are adiabatic tests. Fine (Ref. 1) gives the following relationship between isothermal and adiabatic modulus values for cubic materials:

$$\frac{1}{E_{is}} + \frac{1}{E_{ad}} = \frac{T\alpha^2}{\rho C_p} \tag{3}$$

where:

E_{is}	=	Isothermal modulus of elasticity
E_{ad}	=	Adiabatic modulus of elasticity
T	=	Absolute temperature
α	=	Coefficient of thermal expansion
ρ	=	Density
C_p	=	Specific heat at constant pressure

Fine further states that the difference in modulus values amounts to 0.44 per cent in aluminum, 0.18 per cent in copper, and 0.15 per cent in iron.

The difference between static and dynamic modulus has been attributed to the time dependent relationship between stress and strain. Zener (Ref. 2) has shown that there is an instantaneous relationship between stress and strain called the "unrelaxed elastic modulus" and another relationship occurring after a finite relaxation time called the "relaxed elastic modulus" which has a lower value. In Zener's presentation the stress-strain behavior of a material is determined by $\bar{\tau}$, the mean relaxation time of the material,and ω, which is $2\pi f$, where f is the frequency of stress application. In tests where the product $\bar{\tau}\omega$ is much larger than unity, as with high test speeds, the unrelaxed modulus is obtained. Where the product $\bar{\tau}\omega$ is much less than unity, the relaxed modulus value would be obtained. In the region where $\bar{\tau}\omega$ is close to unity, an intermediate value of modulus results. Zener has shown that for several metals, $\bar{\tau}$ is on the order of .0005 to .006 seconds. Thus in the dynamic modulus tests in this program the unrelaxed modulus would be determined. Richards (Ref. 3) indicates that the relaxation rate may be stress dependent and that the modulus is a function of stress, decreasing as stress increases. Since the nominal stress applied by the driving voltage was of the order of 6×10^{-7} psi*, the stress involved in the dynamic modulus tests conducted in this program never exceeded 0.01 psi even if the resonance amplification raised the stress level by a

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*Using the equation for force between plates of a parallel plate condensor as follows:

$$F = \frac{V^2 \epsilon_v \epsilon_r A}{2X^2}$$

Where:

V	=	Peak voltage applied (approximately 212 volts in this program)
ϵ_v	=	dielectric constant of vacuum
ϵ_r	=	relative dielectric constant of air (1.0)
A	=	Area of specimen end (approximately 0.049 sq. in.)
X	=	Separation between specimen and driving plate (approximately 0.01 mm minimum)

factor of 10^4. Thus it would be expected that the modulus obtained by the dynamic test would be higher than that in the static test where the stress levels were five orders of magnitude higher.

Since the modulus obtained in the dynamic test is different from that obtained in static tests, the usefulness of the data is determined by the intended application. From a design viewpoint, where moderate to high stress levels are generally encountered, the dynamic modulus represents an upper limit of modulus which could be expected under conditions of rapid loading. As a research tool, the dynamic modulus test offers sufficient sensitivity and precision to be used in metallurgical studies and at the same time permits the use of small, simple specimens.

TEST EQUIPMENT

General Description of Test Equipment

The apparatus used in the dynamic elastic modulus determinations consists of equipment for exciting the specimen and detecting and measuring the resonant frequency while the specimen is held at the desired test temperature. Figure 1, is a block diagram of the equipment used in the determinations. A close-up view of a specimen mounted in the apparatus is shown in Figure 2. The exciting frequency is produced by a sine wave signal generator which has a frequency range of 20 to 200,000 cycles per second. The signal is amplified by a power amplifier and fed into the test fixture through a step-up transformer. An electronic counter with an accuracy of $\pm$ 1 cps is used to monitor the frequency of the input signal. In the test fixture, described later in more detail, the drive signal is applied between a plate parallel to the end of the specimen and ground. Longitudinal vibrations are set-up in the specimen which is at ground potential. At the pick-up end of the specimen a plate is biased above ground potential by a DC voltage. This plate and the end of the specimen form a capacitor. As the end of the specimen oscillates longitudinally the capacity varies and an alternating voltage is produced. This AC signal, which is proportional to the amplitude of vibration of the end of the specimen, is amplified by a pre-amplifier and fed to an oscilloscope, and to an electronic frequency counter. When the specimen is driven into resonance, as indicated by the large signal on the oscilloscope, the resonant frequency is indicated by the electronic counter.

Construction of Test Fixture and Pre-amplifier

The test fixture is illustrated in a sectional view in Figure 3. The supporting structure consists of three equilaterally spaced bars of Type 301 stainless steel supported by stainless steel cross-plates. The center cross member is drilled and tapped for three Udimet 500 screws which support the specimen at its mid-point. Stainless steel tubes are used to carry the capacitor plates. The tubes are supported as shown at A in Figure 3 by boron nitride sleeve bearings. The positions of the tubes are adjusted longitudinally by hand wheels located outside the furnace at B. The capacitor plates, made of platinum to prevent scaling at high temperature, are supported by ceramic seats at the tube ends. Electrical connection to the plates is made through stainless steel rods running longitudinally through the tubes.

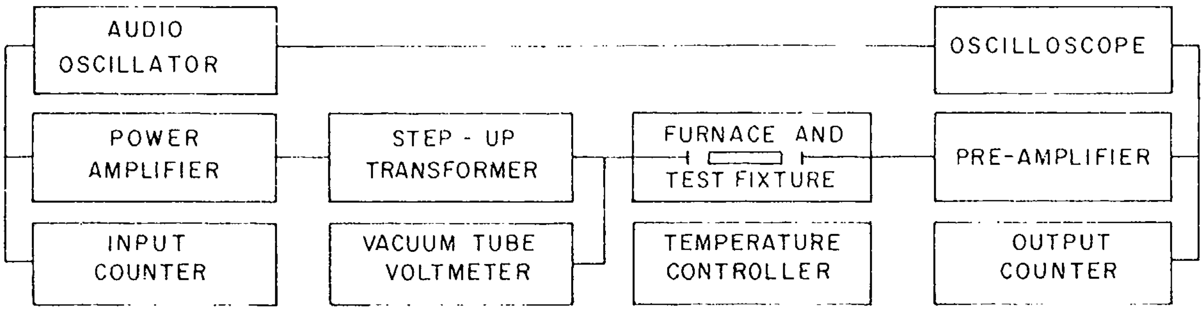

Figure 1. Block Diagram of Dynamic Elastic Modulus Apparatus

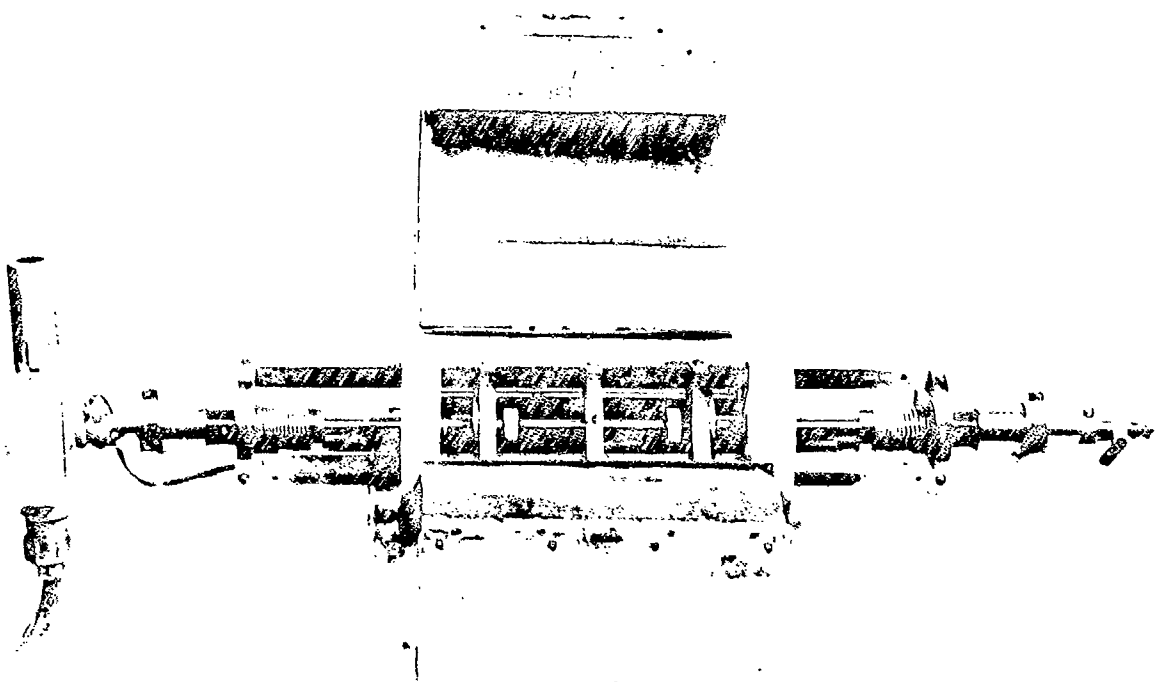

Figure 2. Furnace and Test Fixture

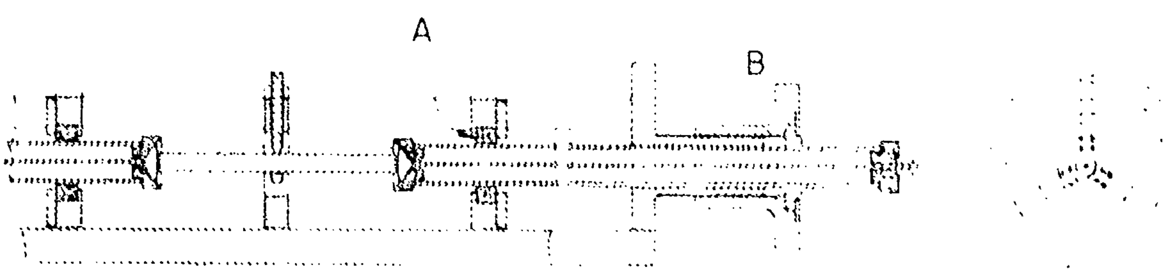

Figure 3. Sectional View of Test Fixture

The pre-amplifier in the test setup was specially constructed for use with the dynamic modulus apparatus. It consists of a cathode follower stage which mounts on the end of the test fixture, two or three stages of R-C coupled amplifiers (switch selected to provide high or low gain), and a cathode follower output stage. The pre-am :ier is battery powered to minimize hum. Overall gain of the unit is approximately 55 db on low gain and approximately 85 db on high gain. The cathode follower first stage, which may be seen in Figure 2, serves as an impedance transformer to provide a low impedance source to the cable to the pre-amplifier in order to minimize noise pickup and loss of high frequency signal. The. D.C. bias necessary for operation of the capacitor pickup is provided by the pre-amplifier power supply.

EXPERIMENTAL PROCEDURES

Specimen Preparation

The specimens for dynamic modulus tests were nominally 1/4-inch diameter, 3-inch long cylindrical rods. Although a wide variety of shapes was possible, it was desirable that the length-to-diameter ratio be at least 10. Also, this size allowed a specimen to be made from a small sample, such as a jet engine blade.* It was required that the specimen be of uniform cross-section and that the end surfaces be flat and perpendicular to the specimen axis. Specimen preparation involved machining the uniform cross-section, cutting off the portion of the ends drilled for lathe centers, and grinding the end surfaces. These surfaces were then polished using fine grades of polishing paper.

Specific Gravity Determinations

In the equation relating modulus to resonant frequency, only two physical quantities of specimen are needed, i.e., the length and specific gravity (or density). The lengths were determined directly with a 3-inch micrometer. Specific gravity determinations were accomplished by the method of measuring the loss of weight in CCl_4. For a few specimens, densities were determined by weighing and measuring the volume.

Specimen Installation

The specimens were supported in the test fixture by three clamping screws located around the specimen at its midlength, the nodal point for fundamental resonance. Experiments showed that exact location of the screws was not necessary and . tightening or loosening the screws had no measurable effect upon the resonant frequency of the specimen. For temperature measurements it was necessary to maintain a thermocouple in contact with the specimen. The thermocouple bead was tied to the specimen at its midpoint with asbestos string. In addition to supporting the specimen, the clamping screws provided a ground connection which kept the specimen at ground potential. This electrical contact was adequate for the first few tests until the clamping screw threads oxidized making the electrical contact unreliable or even impossible. This problem was eliminated by capacitance-welding a 28-gage chromel or alumel wire to the specimen at midlength and making the ground connection outside the furnace. Once the specimen was installed, the apparatus was placed in a standard nichrome-wound split-shell furnace with a liner for optimum temperature distribution.

* Two samples of Udimet 700 were actually taken from jet engine turbine blade castings.

Operating Practices

Once the room temperature dynamic modulus was determined, the apparatus was heated at the average rate of about 12 degrees per minute. Resonant frequencies were determined while the temperature was increasing, by observing the temperature and frequency as the response amplitude reached a peak. The dynamic modulus was determined in this way for each material to temperatures considered above the useful range for the material. At temperatures above 1000°F, differential thermal expansion caused the specimen to loosen; it was corrected by opening the furnace long enough to tighten a clamping screw. This practice was necessary on most tests but had no detectable effect upon the response curve of the material. If the specimen clamping screws were not tightened the specimen would be free to shift and tilt; it would be so misaligned at 1300-1400°F that no resonance could be detected. Thus, it was impossible to obtain data above these temperatures on materials that required an inert atmosphere. Inert atmospheres were obtained by flushing the closed furnace with 10-20 cubic feet of helium per hour.

Static Modulus Determinations

For comparison purposes, the room temperature static modulus was determined for all materials where tensile specimens could be made from the same stock. Therefore the specimens used were primarily tensile specimens with a 2 1/8-inch gage length 0.4 inches in diameter with 9/16-18 NF threaded grips. A few specimens with a 2 1/8-inch gage length, 0.3 inches in diameter with 1/2-20 NF threaded grips were used where stock size was limited. Tests were made in a Baldwin 20,000-pound tensile machine having a certified calibration of ± 1 per cent in the load range used. Extension was measured with Tuckerman optical strain gages. Spherical seat pullrods were used but eccentric loading was still a problem. Strains indicated on opposite sides of the specimen were averaged to obtain the overall strain for the stress-strain plot. Static modulus values reported indicate the slope of the best straight line that could be fitted to the tensile data.

ACCURACY OF TEST PROCEDURES

Accuracy of Dynamic Modulus Values

In analyzing the accuracy of the values of dynamic modulus, two types of possible errors must be considered: (1) errors in measurement, and (2) errors introduced by simplifying assumptions. Possible sources of error in measurement are encountered in the determination of specimen length, density or specific gravity, and resonant frequency. Errors introduced by simplifying assumptions include neglecting the effect of Poisson's ratio and damping terms in the general equation for modulus, and neglecting the effect of thermal expansion on specimen dimensions. Each of the possible sources of error are discussed below:

(1) Specimen measurement. The specimens were measured with a 2-3 inch micrometer which could be read to ± 0.0001 inch. However, difficulty in aligning the specimen in the micrometer limited the reproducibility of measurement to ± 0.01 per cent of the three-inch-long specimen. Since the length squared is used in the equation for modulus, the error in length measurement would introduce a possible error of ± 0.02 per cent in modulus value.

(2) Density measurement. In most cases the density of each specimen was determined by making a loss of weight in fluid determination of the specific gravity. The determinations were made in an analytical balance reading directly to 0.001 gram, using carbon tetrachloride of known specific gravity as a reference fluid. The two weight measurements were accurate within ± 1 part in approximately 15,000, and the specific gravity of the carbon tetrachloride was known within ± 1 part in 3,000. The accuracy of the specific gravity determinations was ± 0.05 per cent.

(3) Frequency measurement. The resonant frequency was determined by counting frequency with an electronic counter, at peak signal amplitude. The accuracy of the counter is ± 1 count (± 1 cycle per second), and the amplitude peak could be determined, by observation of the signal on the oscilloscope, within ± 5 cps. Thus the maximum error in resonant frequency determination was ± 6 cps or ± 0.04 per cent the frequency range of the tests which was usually from about 30,000 cps down to 15,000 cps. Since the second power of the resonant frequency is used in the formula for dynamic modulus, the maximum error in modulus value contributed by this term was ± 0.08 per cent.

(4) Poisson's ratio. Since the longitudinal vibrations of the specimen are accompanied by transverse contractions the complete formula for modulus must contain a correction for Poisson's ratio as given below:

$$E = \frac{4L^2}{n^2} \rho f_n^2 \left(1 + \frac{n^2 \pi^2 \sigma^2 r^2}{2L^2} \right) \qquad (4)$$

where:

L	=	Specimen length
n	=	Number of half wave lengths, indicating mode of vibration (n = 1 in the test described in this report)
ρ	=	Density
f_n	=	Resonant frequency
σ	=	Poisson's ratio
r	=	Specimen radius

For most of the materials investigated in this program, Poisson's ratio is approximately 0.3, thus the equation may be reduced to:

$$E \cong 4L^2 \rho f_n^2 \left(1 + .444 \left(\frac{r}{L}\right)^2 \right) \qquad (5)$$

The dimensions of the test specimen used in this program were: r = .125 inches and L = 3.00 inches. Therefore the correction factor, $\left(1 + .444\left(\frac{r}{L}\right)^2\right)$, would be 1.00077.

Thus, simplification of the dynamic modulus formula by neglecting the effect of Poisson's ratio, would introduce an error of -.07% in the value of dynamic modulus.

(5) Damping. The dynamic modulus is affected by internal friction, or damping, of the specimen as follows:

$$E = \frac{4L^2}{n^2} \rho f_n^{\ 2} \left(\frac{1}{1-\left(\frac{1}{8Q^2}\right)} \right)^2 \qquad (6)$$

where:

Q^{-1} (Damping) = $\Delta f / f_n$ where f_n is the resonant frequency and Δf is the width of the resonant peak at $\sqrt{2}/2$ of peak amplitude.

L, ρ, f_n and n are as previously defined.

In the experimental program a limited number of observations of Q^{-1} were made by measuring bandwidth at the half power points of the resonance curve. The values of Q^{-1} observed where in the range 0.001 to 0.015, which resulted in a negligible damping correction. Therefore no attempt was made to determine damping on all specimens tested in the program. It can be shown that a Q^{-1} of 0.060, which represents four times the maximum bandwidth of resonance peak observed in the program introduces a negative error of less than 0.1% in the value of modulus.

(6) Coefficient of Expansion. The modulus values in this report have been calculated at room temperature values of length and density. Since both length and density are affected by thermal expansion, a more correct value of modulus may be obtained by considering the coefficient of thermal expansion. Graft, Levinson, and Rostoker (Ref. 4) have developed a mathematical derivation of a correction factor to be applied to the modulus formula to obtain elevated temperature values using room temperature measurements. The corrected formula appears as follows:

$$E_t = \frac{4L^2}{n^2} \rho f_n^{\ 2} \left(\frac{1 + 2\alpha T}{1 + 3\alpha T} \right) \qquad (7)$$

where:

E_t = Modulus at temperature t

α = Linear coefficient of thermal expansion

T = Temperature difference, t - (room temperature)

L, ρ, f_n, and n are as previously defined.

Since the modulus values reported herein were not corrected for the effect of thermal expansion, errors are present ranging in value up to approximately plus 1.2% for cobalt and nickel base alloys in the vicinity of 1800°F. If desired the modulus values reported may be corrected for thermal expansion by using equation (7).

In addition to the known sources of error given above, a possible source of error could be encountered when clamping the specimen in the test fixture. The resonant frequency is affected by damping introduced by clamping the specimen at a slight distance from the node. An indication of the size of this error was obtained by conducting several room temperature resonant frequency determinations on a specimen while removing the specimen and replacing it in the fixture between each determination. The maximum deviation is observed resonant frequency was less than ± 15 cps. This represented a maximum error of ± .05 per cent of the resonant frequency which would contribute an error of ± 0.1 per cent to the room temperature modulus value.

Accuracy of Test Temperature

During dynamic modulus determinations the temperature of the test specimen was measured by a thermocouple tied to the specimen with asbestos string at the mid-point location of the clamping screws. Prior to the test program the temperature distribution along a specimen and a correction factor for the measuring thermocouple were established using dummy specimens. These specimens had fine thermocouples welded to the specimen near each end and at the mid-point.

The furnace used in the program had three heating zones each of which was powered by a variac. Using the dummy specimens, the variac settings necessary to give the most uniform temperature along the specimen were determined. By this means the maximum spatial temperature deviation was limited to ± 4°F.

The test temperature, as measured by the thermocouple tied to the specimen and indicated on an electronic potentiometer-type recorder was found to differ from the actual specimen temperature as measured by the thermocouple welded to the specimen mid-point. This difference was attributed to the effects of the clamping screws and the asbestos string used to fasten the indicating thermocouple. In several tests with dummy specimens a curve of temperature correction vs. indicated temperature was established. The corrections established by this curve were used in determining test temperatures for the plots of modulus vs. temperature. The accuracy of test temperatures established in this manner was ± 3°F.

DATA SHEETS

The following 51 pages are data sheets containing the information known about the materials tested as well as a graphical presentation of the elevated temperature dynamic modulus test results. Total information pertaining to each material is given on a separate page, along with an applicable curve.

The designation of commercial alloys is the commercial name, wherever applicable.

Actual compositions were obtained wherever possible. The majority of the analyses given were performed on submitted samples in a commercial laboratory. In several instances the manufacturer's heat analysis is used. Composition limits are provided

when known, for comparison purposes, and references are made to the source of information. Where composition limits are not known a nominal or typical analysis is given. All values reported are in weight percentage.

Most materials were heat treated to the condition most commonly used. The condition of heat treatment is given. Non-heat-treatable materials were tested in the annealed condition or in the condition in which they were supplied. Where the "as-received" condition was not known, hardness tests were performed and the material condition determined from the literature.

Specific gravity data had to be obtained since this value is required in solving the equation relating modulus to resonant frequency. Specific gravity determinations were made by the method of measuring the loss of weight in CCl_4. In some cases density was determined by weighing and measuring the volume.

The authors' comments on the response of a material to dynamic modulus tests are given under the heading, discussion.

A room temperature comparison of dynamic modulus with static modulus is provided where tensile specimens could be fabricated from the same stock.

Finally, each page displays the modulus-temperature plot for that material. Individual data points are shown.

HIGH-PURITY ALUMINUM

Composition:

	Actual, %	Nominal, %
Aluminum	99.994	99.999

Heat Treatment:

As cold-rolled (1/2-inch plate)
Specimens annealed 750 F, 1 hour, air cooled

Specific Gravity: 2.699

Room Temperature Dynamic Modulus:
9.97×10^6 psi

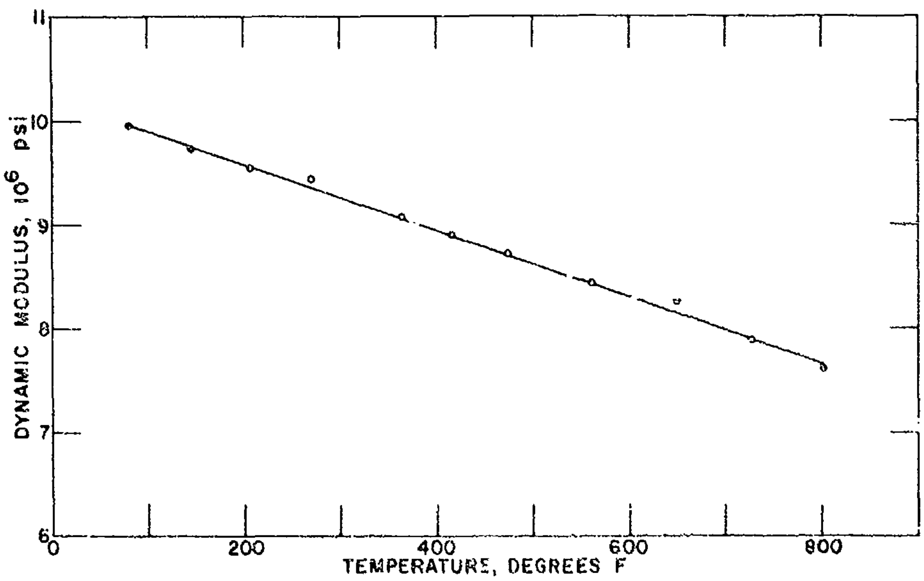

Figure 4. Dynamic Modulus as a Function of Temperature for High Purity Aluminum (As Cold Rolled)

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2024 - T4

Composition:

	Actual, %	Limits, % (Ref. 5)	
Copper	4.30	3.8-4.9	
Iron	0.28	0.50 max	
Silicon	0.17	0.50 max	
Magnesium	1.32	1.2-1.8	
Manganese	0.62	0.30-0.90	
Zinc	0.06	0.25	
Chromium	0.02	0.10 max	
Titanium	0.02	0.05 max	total 0.15 max
Nickel	< 0.02	0.05 max	
Lead	< 0.05	0.05 max	
Tin	< 0.05	0.05 max	
Other Elements	—	0.05 max	
Aluminum	Balance	Balance	

Heat Treatment:

T-4 condition (solution heat treated and naturally aged) Material had been stored at room temperature about eight years. Hardness R_B 75

Specific Gravity: 2.786

Discussion:

Three samples of 2024 -T4 were tested to establish the reproducibility of the data. For all three samples the modulus - temperature plot indicates the presence of a "hardening" phase at lower temperatures with the effect vanishing at about 500 F. It is postulated that the decrease in modulus is a result of the solution of an aluminum - copper - manganese precipitate, probably $Cu_2 Mg_2 Al_5$. Data on the solubility of this phase at various temperatures was not readily available, and a metallographic study was beyond the scope of this program.

Room Temperature Modulus:

Static: 10.6×10^6 psi

Dynamic: 10.78×10^6 psi (average of 3 samples)

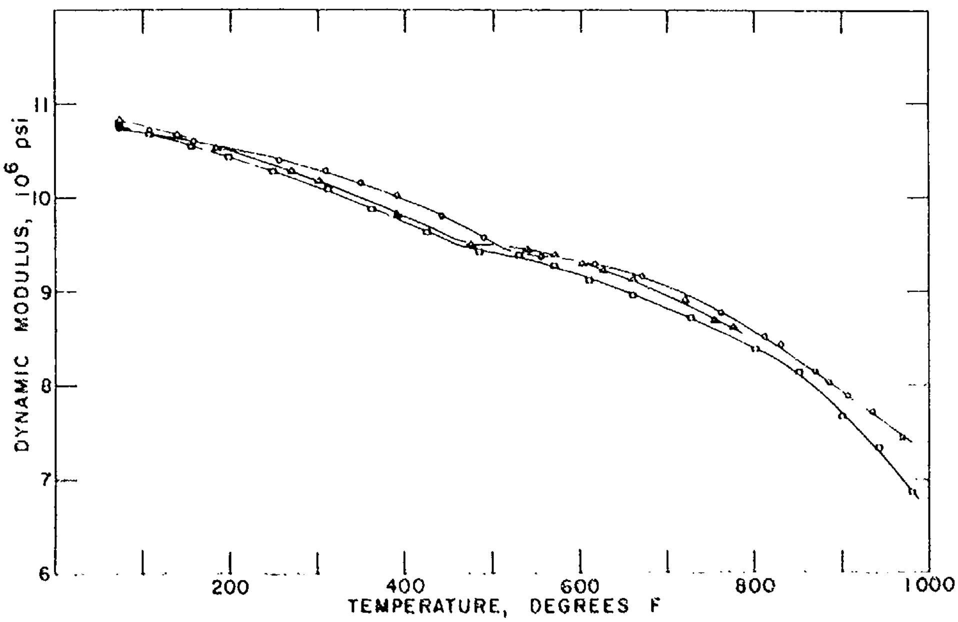

Figure 5. Dynamic Modulus as a Function of Temperature for 2024 - T4 (3 Samples)

7075 - T6

Composition:

	Actual, %	Limits, % (Ref. 6)	
Copper	1.34	1.2-2.0	
Iron	0.25	0.7 max	
Silicon	0.20	0.50 max	
Magnesium	2.44	2.1-2.9	
Manganese	0.06	0.30 max	
Zinc	5.39	5.1 - 6.1	
Titanium	0.06	0.20 max	
Chromium	0.21	0.18-0.40	
Nickel	< 0.02	0.05 max	total
Lead	< 0.05	0.05 max	0.15
Tin	< 0.05	0.05 max	max
Other Elements	——	0.05 max	
Aluminum	Balance	Balance	

Heat Treatment:

T-6 Condition (Solution Heat Treated and Artificially Aged)

Specific Gravity: 2.804

Room Temperature Modulus:

Static: 10.4×10^6 psi

Dynamic: 10.65×10^6 psi

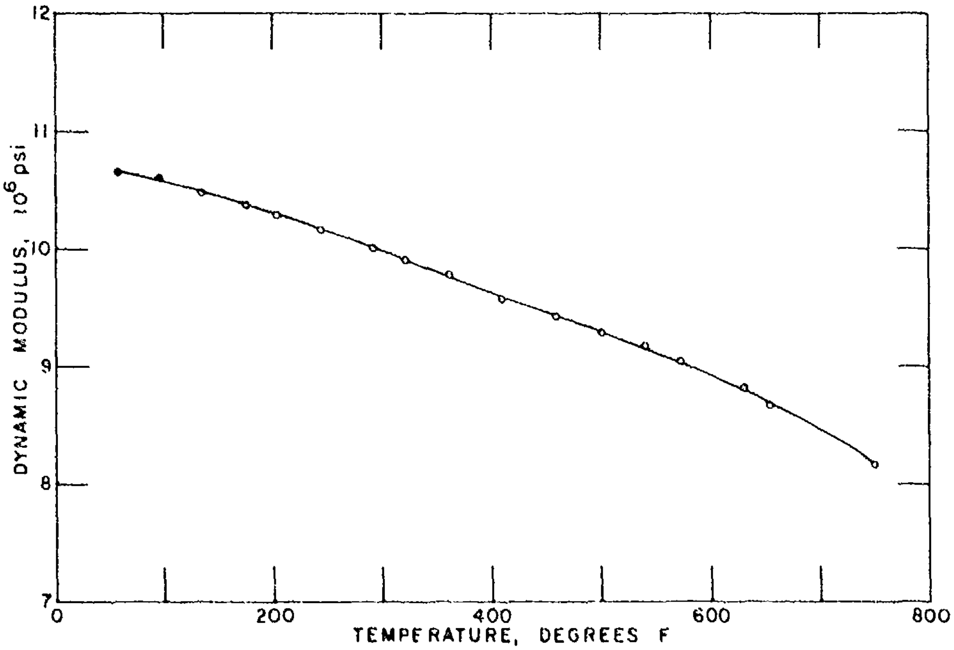

Figure 6. Dynamic Modulus as a Function of Temperature for 7075 - T6

COMMERCIAL PURITY BERYLLIUM

Composition:
Commercial Purity

Heat Treatment:
As Hot Pressed

Specific Gravity: 1.865

Discussion:
Because of its toxicity, beryllium could not be exposed to temperatures greater than 1200 F without special facilities.

Room Temperature Dynamic Modulus:
42.65×10^6 psi

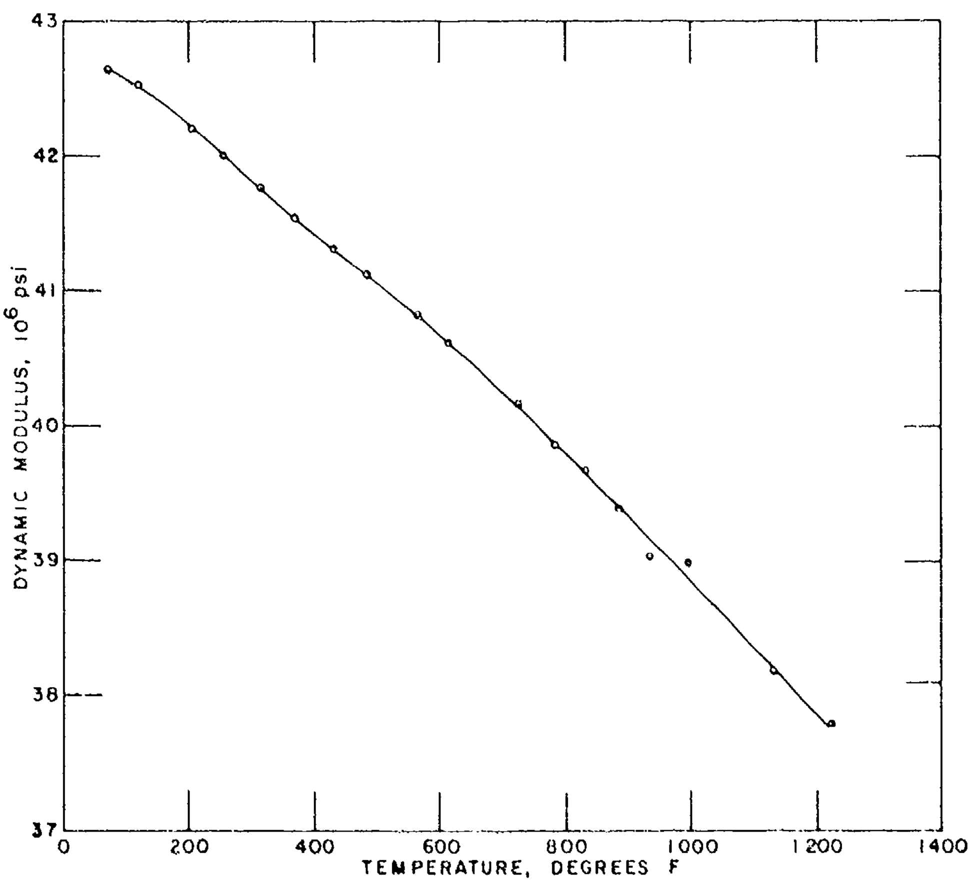

Figure 7. Dynamic Modulus as a Function of Temperature for Commercial Purity Beryllium (Powder Metallurgy)

BERYLLIUM - COPPER

Composition:

	Actual, %	Nominal, %
Beryllium	1.18	1.8-2.05
Nickel	0.008	0.20 min (Ni + Co)
Cobalt	0.13	
Iron	0.12	0.60 max (Ni + Co + Fe)
Copper	Balance	

Heat Treatment:

Condition A

Solution Annealed 1450 F, 1 hour, water quenched. Hardness R_B31

Condition AT

Solution Annealed 1450 F, 1 hour, water quenched. Precipitation Hardened 600F, 3 hours, air cooled. Hardness R_B94.

Specific Gravity: Condition A - 8.512
Condition AT - 8.519

Discussion:

This material was an experimental composition and is considerably lower in Be content than the conventional Be - Copper

Room Temperature Modulus:

	Cond. A	Cond. AT
Static:	17.8×10^6 psi	17.6×10^6 psi
Dynamic:	17.94×10^6 psi	18.02×10^6 psi

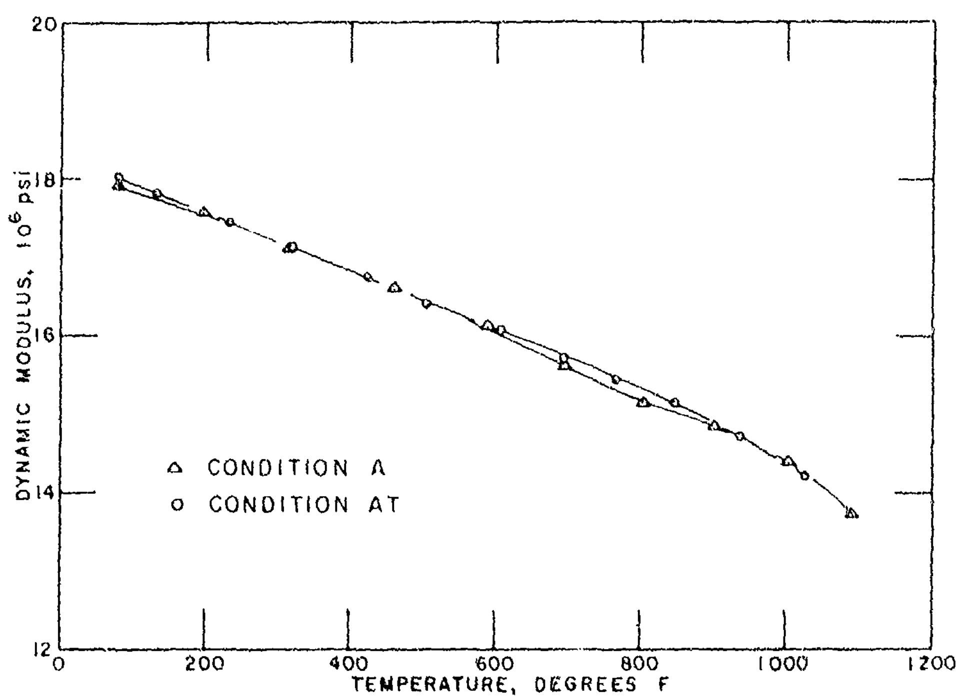

Figure 8. Dynamic Modulus as a Function of Temperature for Beryllium-Copper (Conditions A and AT)

Ti - 6Al - 4V

Composition:

	Actual, %	Limits, % (Ref. 9)
Aluminum	6.0	5.50-6.75
Vanadium	3.0	3.50-4.50
Chromium	0.002	—
Iron	0.2	0.30 max
Titanium	Balance	Balance

Heat Treatment:
Mill Annealed

Specific Gravity: 4.416

Room Temperature Modulus:
Static: 16.4×10^6 psi
Dynamic: 16.52×10^6 psi

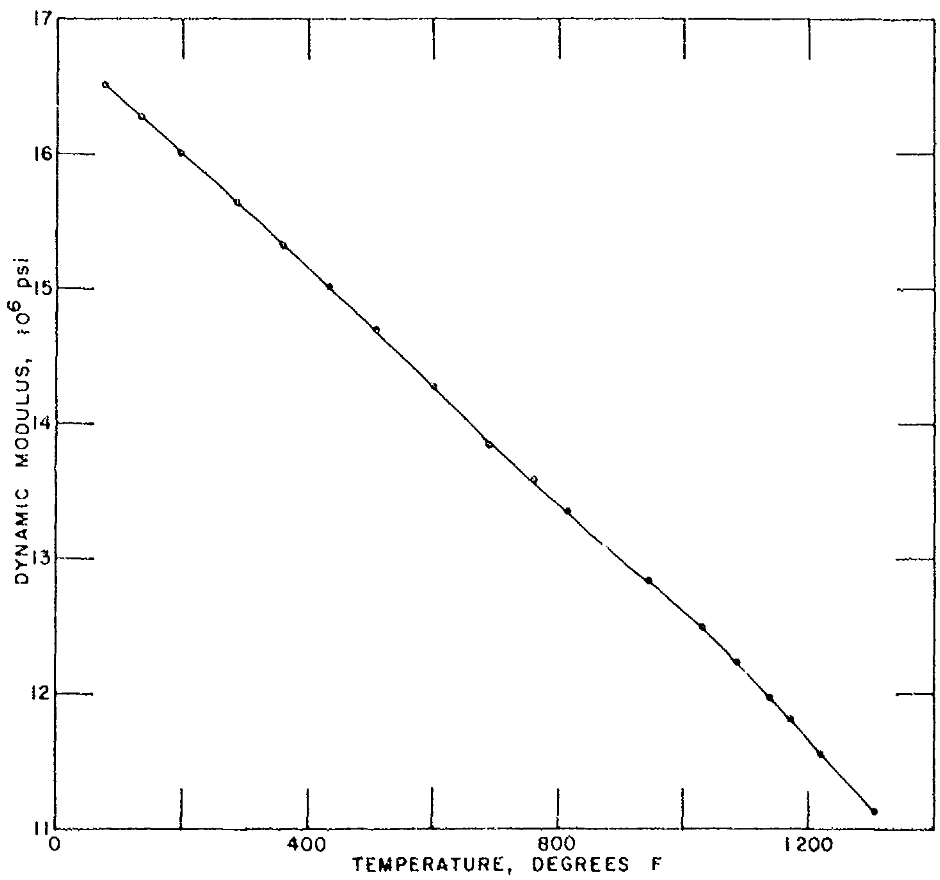

Figure 9. Dynamic Modulus as a Function of Temperature for Ti - 6Al-4V (Annealed)

IODIDE TITANIUM

Nominal Composition:

(Actual composition was not available. The nominal composition given below is considered typical.)

	%
Oxygen	0.01
Nitrogen	0.005
Carbon	0.03
Hydrogen	0.009
Iron	0.02
Titanium	Balance

Heat Treatment:

As-grown condition. The specimen was machined from a 3/4-inch diameter iodide crystal composite.

Hardness VHN 84 (R_B 39 using conversion tables for steels)

Density: 0.163 lb/in^3

Discussion:

The density of this material, as well as Ti-75A, was found by weighing and measuring dimensions. The density was found to be identical to that of the Ti-75A even though several voids could be seen in the microstructure, presumably due to gaps left between crystals during the growing process.

Room Temperature Dynamic Modulus:

12.45×10^6 psi

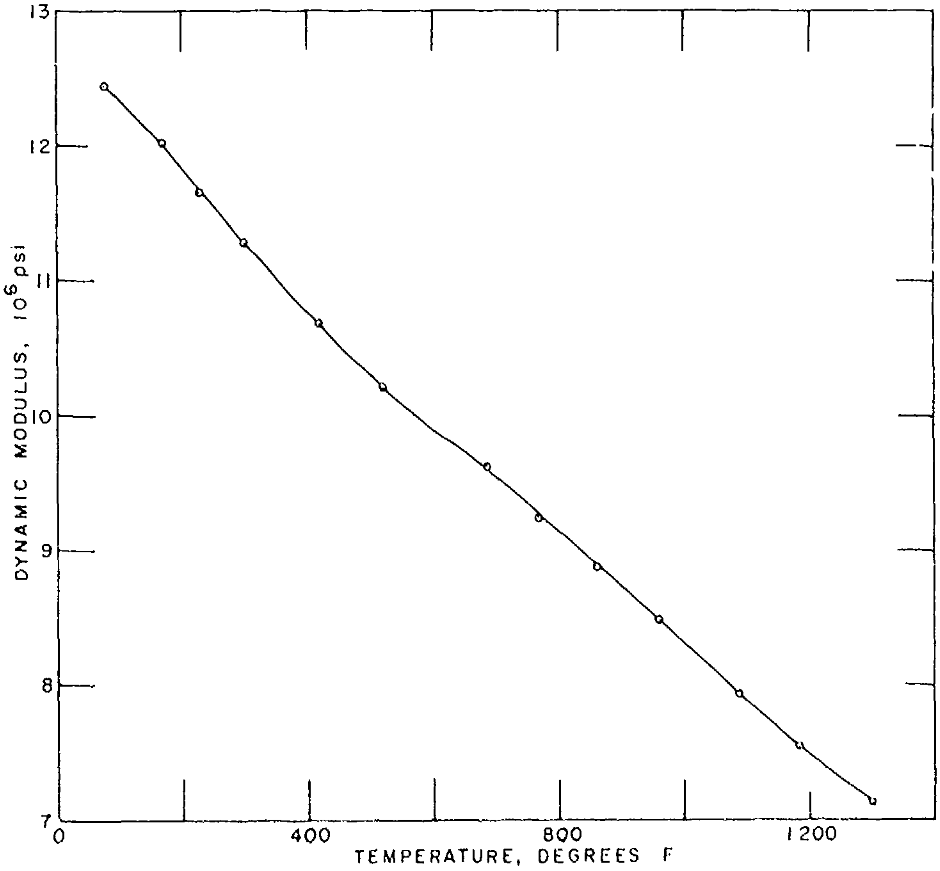

Figure 10. Dynamic Modulus as a Function of Temperature for Iodide Titanium (As Grown)

Ti - 75A

Composition:

	Actual	Limits, % (Ref. 7)
Oxygen	0.19	—
Nitrogen	0.032	—
Carbon	0.04	0.04 max
Hydrogen	0.0321	0.015 max
Iron	0.12	—
Titanium	Balance	Balance

Heat Treatment:

Annealed

Hardness VHN 290 (R_c 28.5 using conversion tables for steels)

Density: 0.163 lb/in^3

Discussion:

Two samples were tested to investigate the reproducibility of the modulus versus temperature curve for this material. An investigation of the observed behavior has been previously reported (Ref. 8). The material was found to consist of two phases, α - Ti and hydride, due to the unusually high hydrogen content. In the temperature range 250-400 F the hydride went into solution, resulting in a change from a two-phase to a single-phase material. The modulus that might be expected from α - ti below 400 F is shown as a dashed line.

Room Temperature Dynamic Modulus:

15.93×10^6 psi

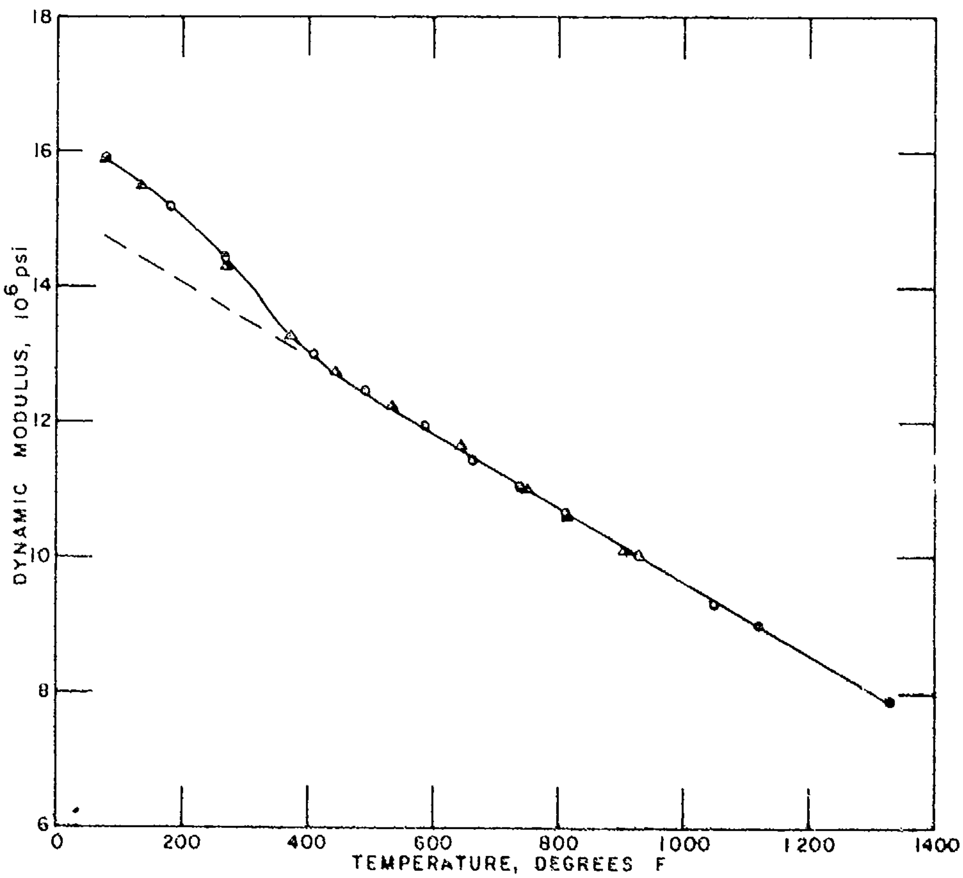

Figure 11. Dynamic Modulus as a Function of Temperature for Ti - 75A (Annealed, 2 Samples)

B-120VCA (Ti-13V-11Cr-3Al)

Composition:

	Actual, %	Limits, % (Ref. 10)
Aluminum	3.7	2.0-4.0
Vanadium	12.5	12.5-14.5
Chromium	10.7	10.0-12.0
Nitrogen	0.02	0.05 max
Hydrogen	0.0090	0.02 max
Carbon	—	0.10 max
Iron	—	0.50 max
Titanium	Balance	Balance

Heat Treatment:
Mill Annealed

Specific Gravity: 4.816

Room Temperature Modulus:
Static: 14.0×10^6 psi
Dynamic: 14.09×10^6 psi

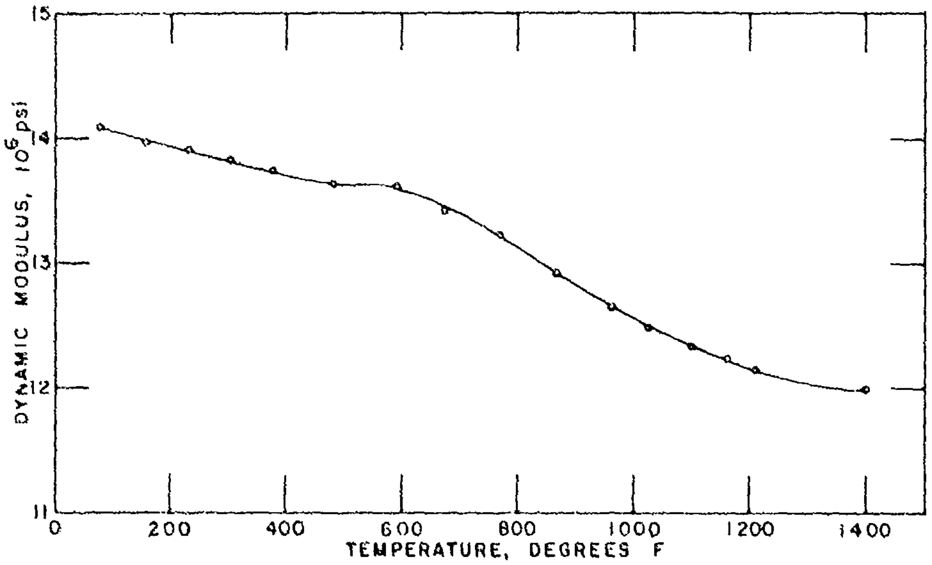

Figure 12. Dynamic Modulus as a Function of Temperature for B-120 VCA (Annealed)

SAE 1020

Composition:

	Actual, %	Limits, %
Carbon	0.24	0.18-0.23
Manganese	0.30	0.30-0.60
Phosphorus	0.01	0.04 max
Sulfur	0.045	0.05 max
Silicon	0.01	—
Iron	Balance	Balance

Material Condition:
As Hot Rolled, Hardness R_B 61

Specific Gravity: 7.839

Room Temperature Modulus:
Static: 30.3 x 10^6 psi
Dynamic: 30.46 x 10^6 psi (average of 2 samples)

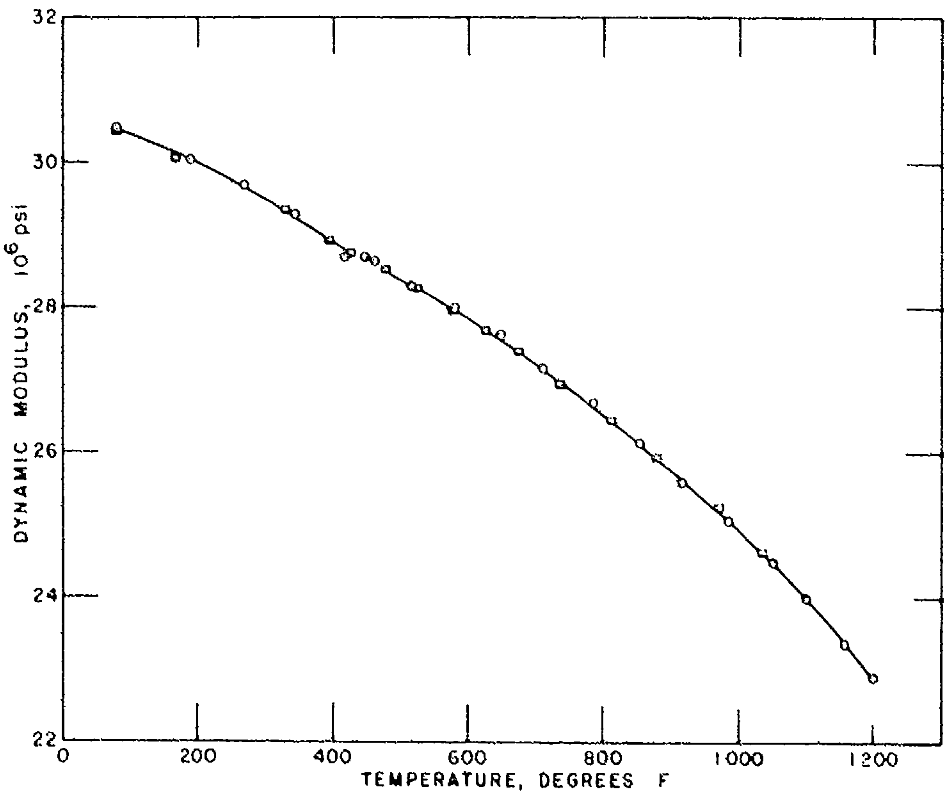

Figure 13. Dynamic Modulus as a Function of Temperature for SAE 1020 (As Hot Rolled, 2 Samples)

SAE 4130

Composition:

	Actual, %	Limits, %
Carbon	0.29	0.28-0.33
Manganese	0.25	0.40-0.60
Phosphorus	0.01	0.040 max
Sulfur	0.012	0.040 max
Silicon	0.16	0.20-0.35
Chromium	0.94	0.80-1.10
Molybdenum	0.17	0.15-0.25
Iron	Balance	Balance

Heat Treatment:
Normalized 1600 F, 30 minutes, air cooled
Tempered 850 F, 1 hour, air cooled

Specific Gravity: 7.832

Room Temperature Modulus:
Static: 31.3×10^6 psi (Heat Treated)
Dynamic: 30.95×10^6 psi (Heat Treated)

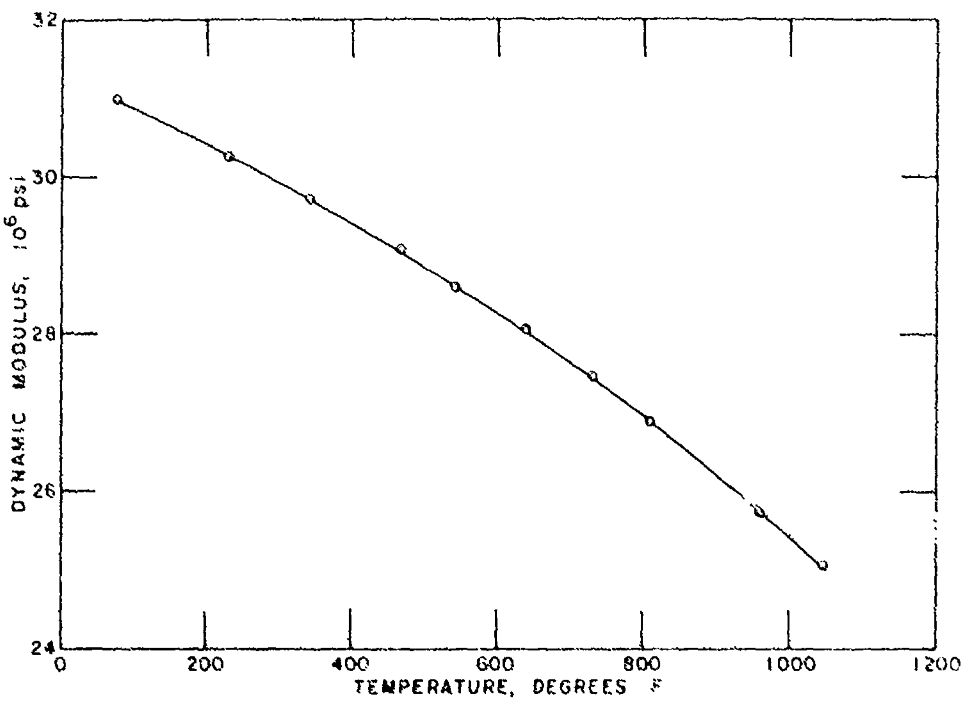

Figure 14. Dynamic Modulus as a Function of Temperature for SAE 4130 (Heat Treated)

SAE 4340

Composition:

	Actual, %	Limits, %
Carbon	0.41	0.38-0.43
Manganese	0.74	0.60-0.80
Phosphorus	0.015	0.040 max
Sulfur	0.015	0.040 max
Silicon	0.26	0.25-0.35
Nickel	1.75	1.65-2.00
Chromium	0.80	0.70-0.90
Molybdenum	0.27	0.20-0.30
Iron	Balance	Balance

Heat Treated:
Austenitized 1550 F, 20 minutes, oil quenched.
Tempered 400 F, 4 hours, air cooled.

Specific Gravity: 7.810

Room Temperature Modulus:
Static: 29.7×10^6 psi (Heat Treated)
Dynamic: 29.68×10^6 psi (Heat Treated)

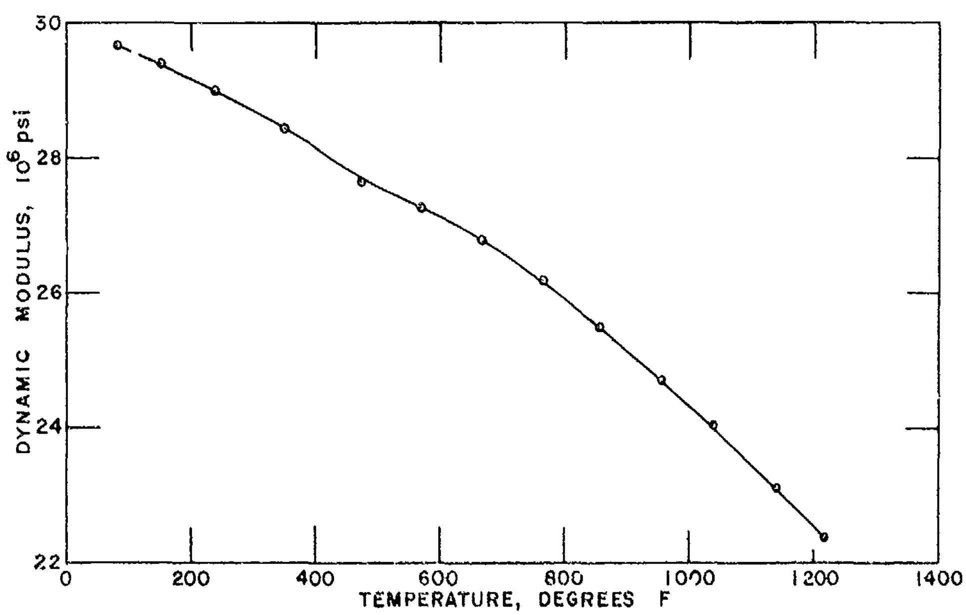

Figure 15. Dynamic Modulus as a Function of Temperature for SAE 4340 (Heat Treated)

LA BELLE HT

Composition:

	Actual, %	Nominal, %
Carbon	0.429	0.43
Manganese	1.39	1.35
Phosphorus	0.013	—
Sulfur	0.021	—
Silicon	0.68	2.35
Nickel	0.13	—
Chromium	1.31	1.35
Molybdenum	0.38	0.40
Vanadium	0.24	0.30
Iron	Balance	Balance

Heat Treatment:

Preheated 1450 F.
Raised to 1700 F, equilibrated, oil quenched.
Tempered 500 F, 2 hours, air cooled.

Specific Gravity: 7.668

Discussion:

Heat treatment of this material decreased the modulus about 1×10^6 psi, an effect which dimished at temperatures above 800 F.

Room Temperature Modulus:

Static: 29.3×10^6 psi (Heat Treated)
Dynamic: 29.59×10^6 psi (Heat Treated)

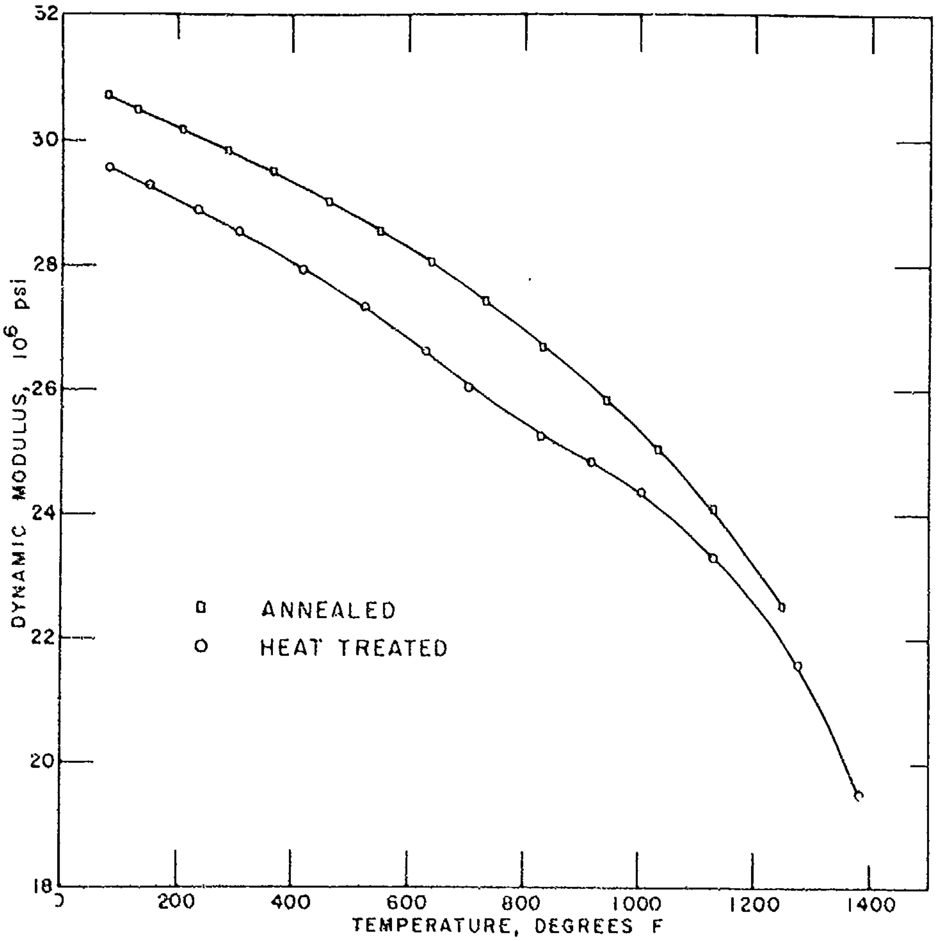

Figure 16. Dynamic Modulus as a Function of Temperature for LaBelle HT (Annealed and Heat Treated)

PEERLESS 56

Composition:

	Actual, %	Nominal, %
Carbon	0.387	0.40
Manganese	0.47	0.55
Phosphorus	0.016	—
Sulfur	0.015	—
Silicon	0.70	1.00
Chromium	3.23	3.25
Nickel	0.16	—
Molybdenum	2.83	2.50
Vanadium	0.24	0.33
Iron	Balance	Balance

Heat Treatment:

Austenitized 1900 F, 1 hour in argon, air cooled.
Double tempered 1000 F, 2 hours, air cooled.

Specific Gravity: 7.782

Discussion:

Heat treatment of this material lowered the modulus 0.6×10^6 psi, an effect which increased slightly with increased temperature

Room Temperature Modulus:

Static: 30.4×10^6 psi (Heat Treated)
Dynamic: 31.28×10^6 psi (Heat Treated)

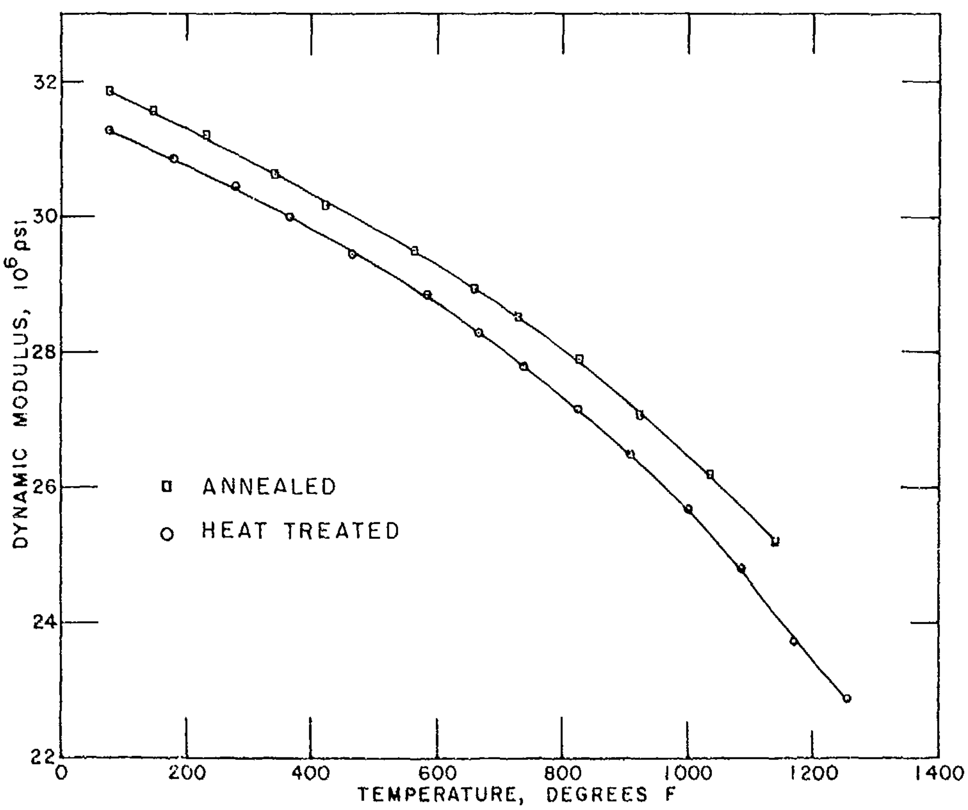

Figure 17. Dynamic Modulus as a Function of Temperature for Peerless 56 (Annealed and Heat Treated)

VASCOJET 1000

Composition:

	Actual, %	Nominal, %
Carbon	0.410	0.40
Manganese	0.17	—
Phosphorus	0.019	—
Sulfur	0.013	—
Silicon	0.80	—
Chronium	5.07	5.0
Molybdenum	1.73	1.30
Vanadium	0.49	0.5
Iron	Balance	Balance

Heat Treatment:
Preheated 1450 F.
Held 30 minutes at 1900 F in argon, air cooled.
Double Tempered 1000 F, 3 hours.

Specific Gravity: 7.722

Room Temperature Modulus:
Static: 30.7 x 10^6 psi (Heat Treated)
Dynamic: 30.70 x 10^6 psi (Heat Treated)

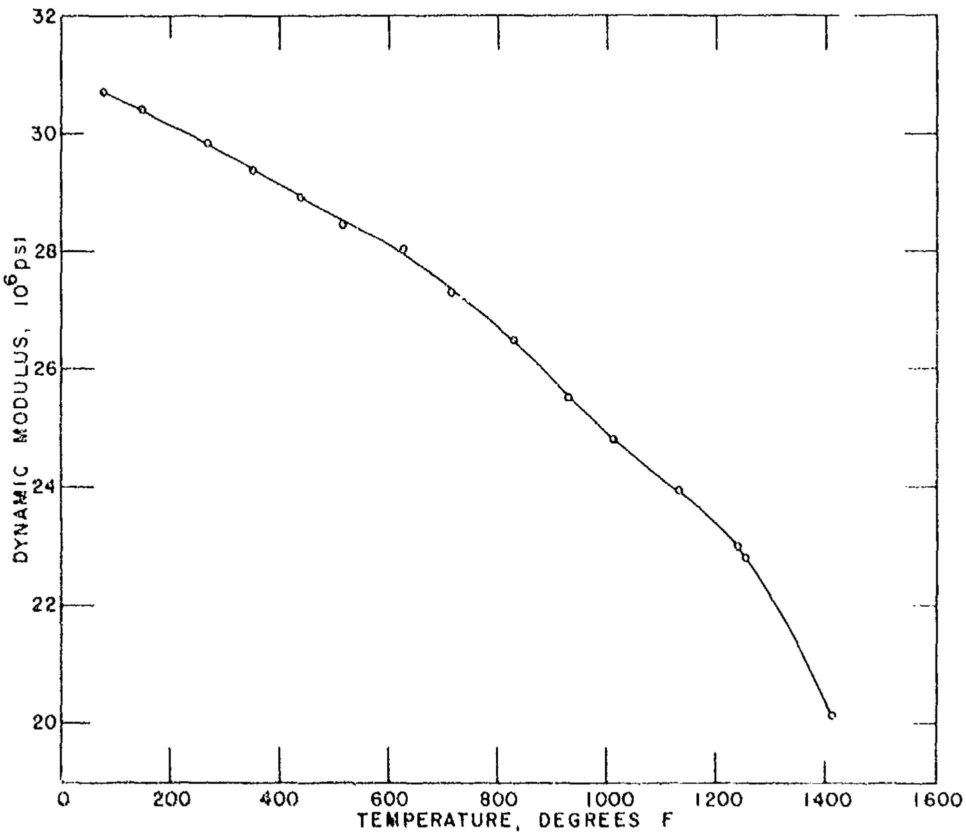

Figure 18. Dynamic Modulus as a Function of Temperature for Vascojet 1000 (Heat Treated)

AISI TYPE 410

Composition:

	Actual, %	Limits, %
Carbon	0.160	0.15 max
Manganese	0.45	1.00 max
Phosphorus	0.019	0.040 max
Sulfur	0.019	0.030 max
Silicon	0.291	1.00 max
Chromium	13.10	11.50-13.50
Nitrogen	0.03	——
Iron	Balance	Balance

Heat Treatment:
1800 F, 30 minutes, air cooled.
Tempered 1075 F, 1 hour, air cooled.

Specific Gravity: 7.717

Room Temperature Modulus:
Static: 32.5×10^6 psi (Heat Treated)
Dynamic: 32.28×10^6 psi (Heat Treated)

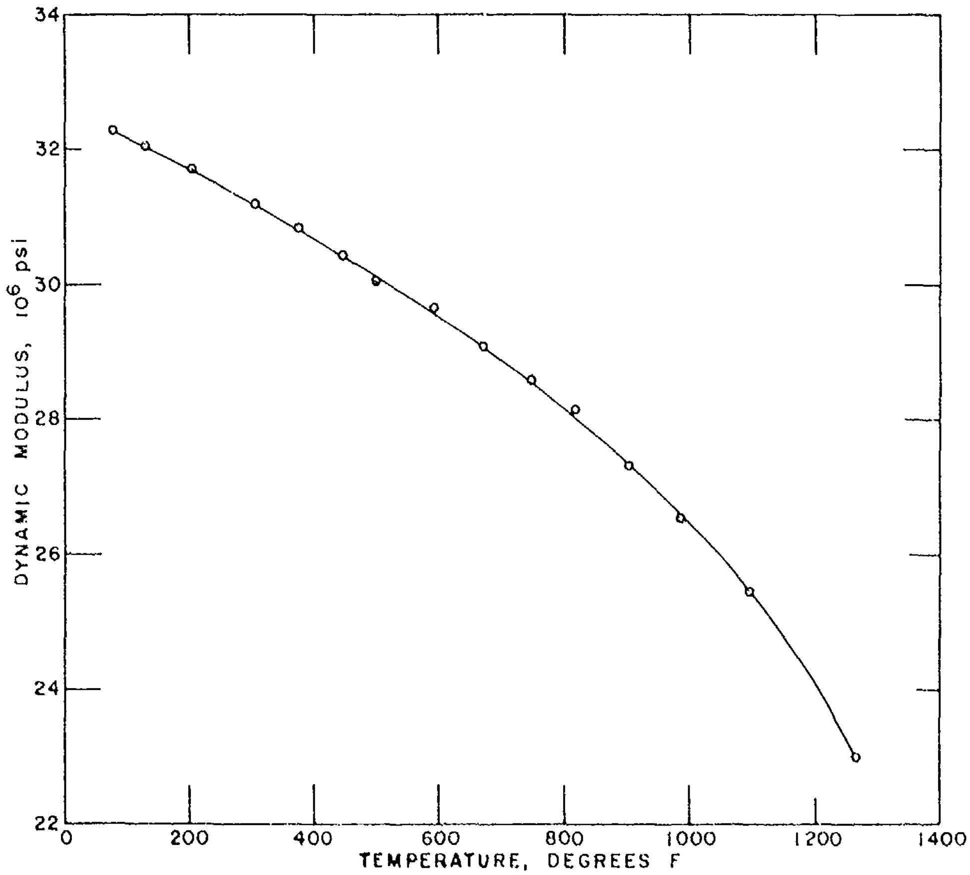

Figure 19. Dynamic Modulus as a Function of Temperature for AISI Type 410 (Heat Treated)

AM 350

Composition:

	Actual, %	Limits, % (Ref. 11)
Carbon	0.100	0.08-0.12
Manganese	1.15	0.50-1.25
Phosphorus	0.026	0.040 max
Sulfur	0.017	0.030 max
Silicon	0.216	0.50 max
Chromium	16.10	16.00-17.00
Nickel	4.55	4.00-5.00
Molybdenum	2.73	2.50-3.25
Iron	Balance	Balance

Heat Treatment:

Allegheny Ludlum designation SCT (850 F) 1725 F, 10 Minutes, air cooled to room temperature. Refrigerated 3 hours, -100 F (dry ice and acetone) 850 F, 3 hours, air cooled

Specific Gravity: 7.785

Room Temperature Modulus:

Static: 29.6×10^6 psi (Heat Treated)
Dynamic: 29.34×10^6 psi (Heat Treated)

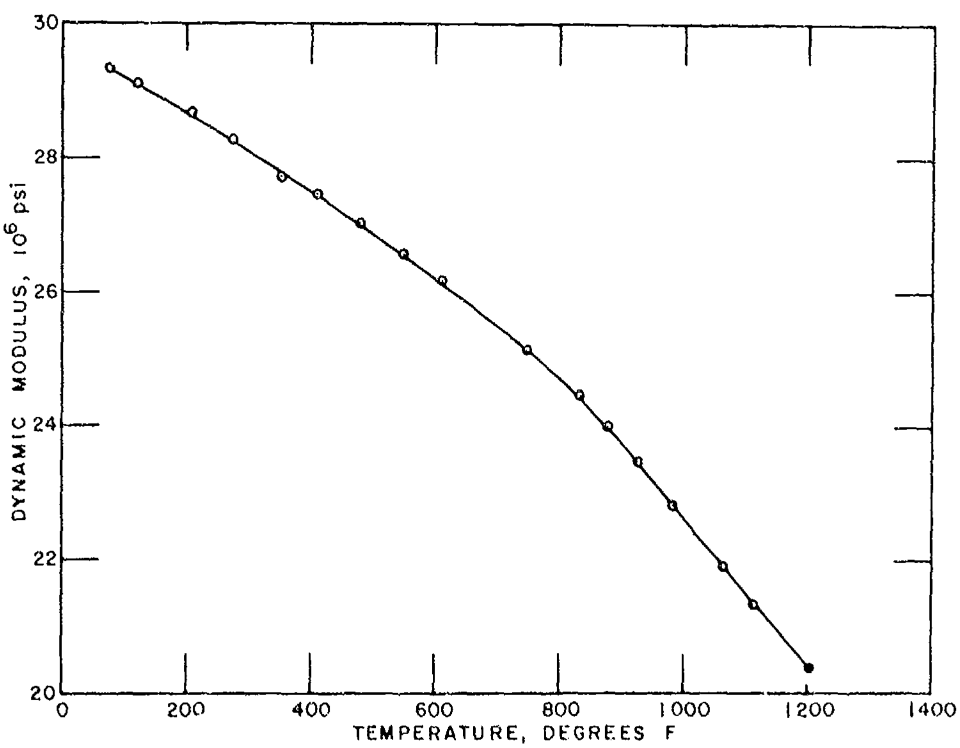

Figure 26. Dynamic Modulus as a Function of Temperature for AM 350 (Heat Treated, SCT 850 F)

TIMKEN 16-25-6

Composition:

	Actual, %	Limits, % (Ref. 14)
Carbon	0.086	0.12 max
Manganese	1.47	2.00 max
Phosphorus	0.019	0.040 max
Sulfur	0.014	0.030 max
Silicon	0.42	1.00 max
Chromium	15.52	15.00-17.50
Nickel	27.02	24.00-27.00
Molybdenum	5.90	5.50-7.00
Vanadium	0.13	——
Iron	Balance	Balance

Heat Treatment:
Annealed, Hardness R_B 97

Specific Gravity: 8.331

Room Temperature Modulus:
Static: 28.9×10^6 psi
Dynamic: 31.98×10^6 psi

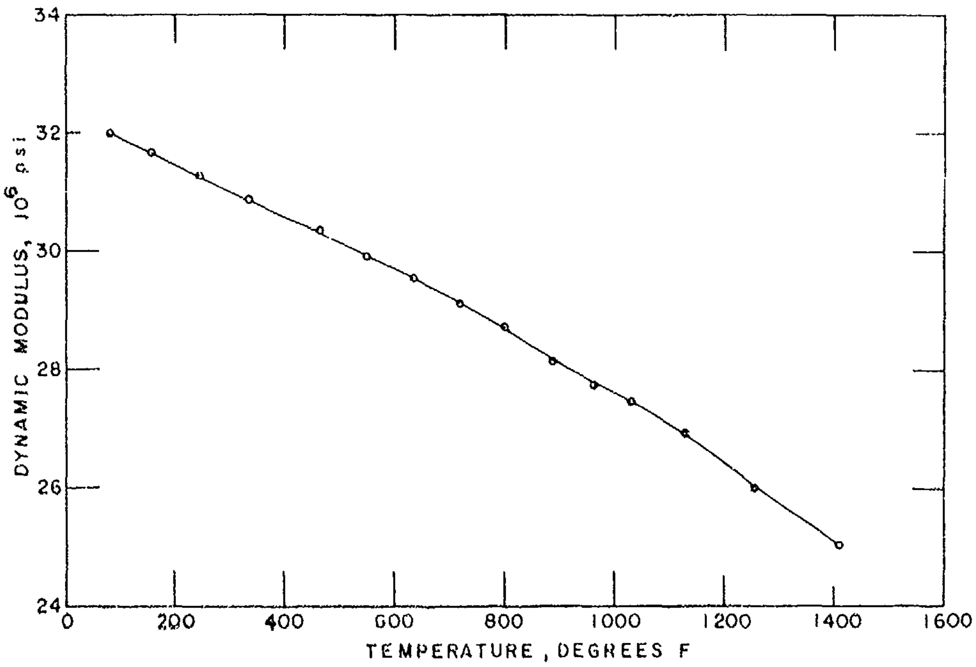

Figure 21. Dynamic Modulus as a Function of Temperature for Timken 16-25-6 (Annealed)

17 - 7 PH

Composition:

	Actual, %	Limits, % (Ref. 12)
Carbon	0.073	0.09 max
Manganese	0.61	1.00 max
Phosphorus	0.023	0.040 max
Sulfur	0.012	0.030 max
Silicon	0.334	1.00 max
Chromium	17.65	16.00-18.00
Nickel	7.20	6.50-7.75
Aluminum	1.13	0.75-1.50
Iron	Balance	Balance

Heat Treatment:

Condition A

Material was received in Condition A, mill annealed at 1900 F

TH 1050 Condition

Transformed 1400 F, 90 minutes, cooled to 60 F within 1 hour, held at 60 F, 30 minutes. Precipitation Hardened 1050 F, 90 minutes, air cooled to room temperature

Specific Gravity: 7.684

Discussion:

The modulus-temperature plot below shows the comparison of conditions A and TH 1050. While the TH 1050 exhibits a modulus 0.7×10^6 psi higher at room temperature, the difference decreases with temperature and the curves intersect at 900 F. Above the precipitation temperature, the moduli of both materials decrease sharply and assume a new slope. Modulus data taken during cooling of the Condition A specimen is shown as a dashed line.

Room Temperature Modulus:

Static: 29.2×10^6 psi (TH 1050)

Dynamic: 29.26×10^6 psi (TH 1050)

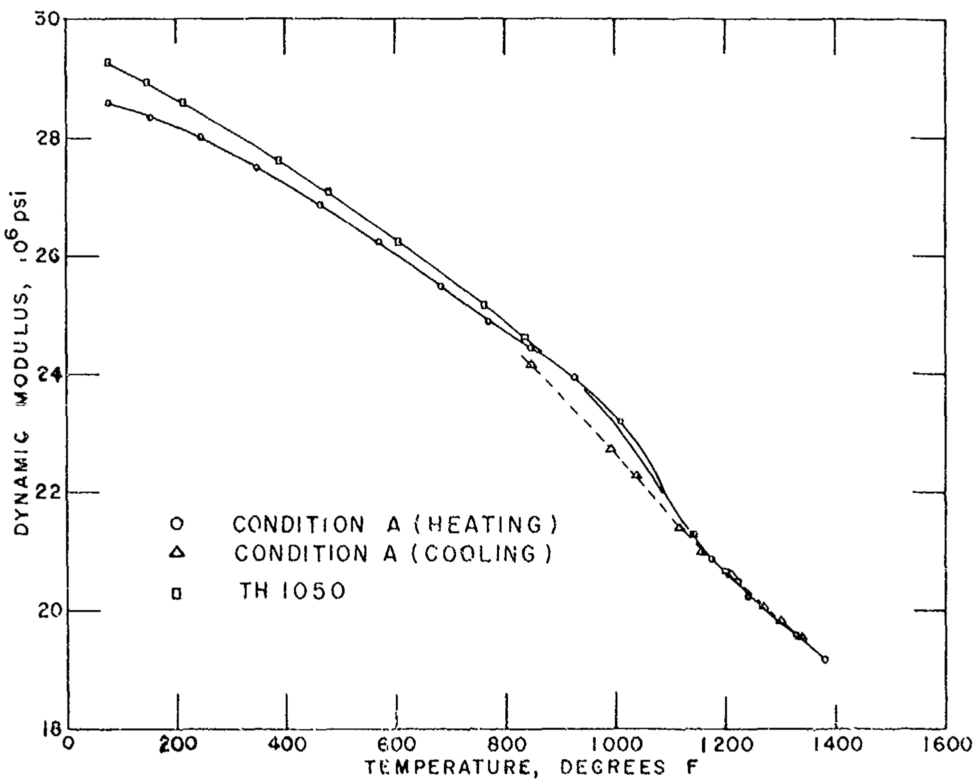

Figure 22. Dynamic Modulus as a Function of Temperature for 17 - 7 PH (Conditions A and TH 1050)

PH 15-7 Mo

Composition:

	Actual, %	Limits, % (Ref. 13)
Carbon	0.075	0.09 max
Manganese	0.70	1.00 max
Phosphorus	0.025	0.040 max
Sulfur	0.018	0.030 max
Silicon	0.390	1.00 max
Chromium	14.10	14.00-16.00
Nickel	7.31	6.50-7.75
Molybdenum	2.27	2.00-3.00
Aluminum	1.24	0.75-1.50
Iron	Balance	Balance

Heat Treatment:

Condition A

Material was received in Condition A, mill annealed at 1900 F

TH 1050 condition

Transformed 1400 F, 90 minutes, cooled to 60 F within 1 hour, held at 60 F, 30 minutes. Precipitation Hardened 1050 F, 90 minutes, air cooled to room temperature

Specific Gravity: 7.758

Discussion:

Heat treatment of this material increased the modulus by 1.4 x 10^6 psi. This effect was stable up to the precipitation hardening temperature but decreasing above that with the TH 1050 curve approaching the Condition A curve above 1400 F.

Room Temperature Modulus:

Static: 29.1 x 10^6 psi (TH 1050)

Dynamic: 29.39 x 10^6 psi (TH 1050)

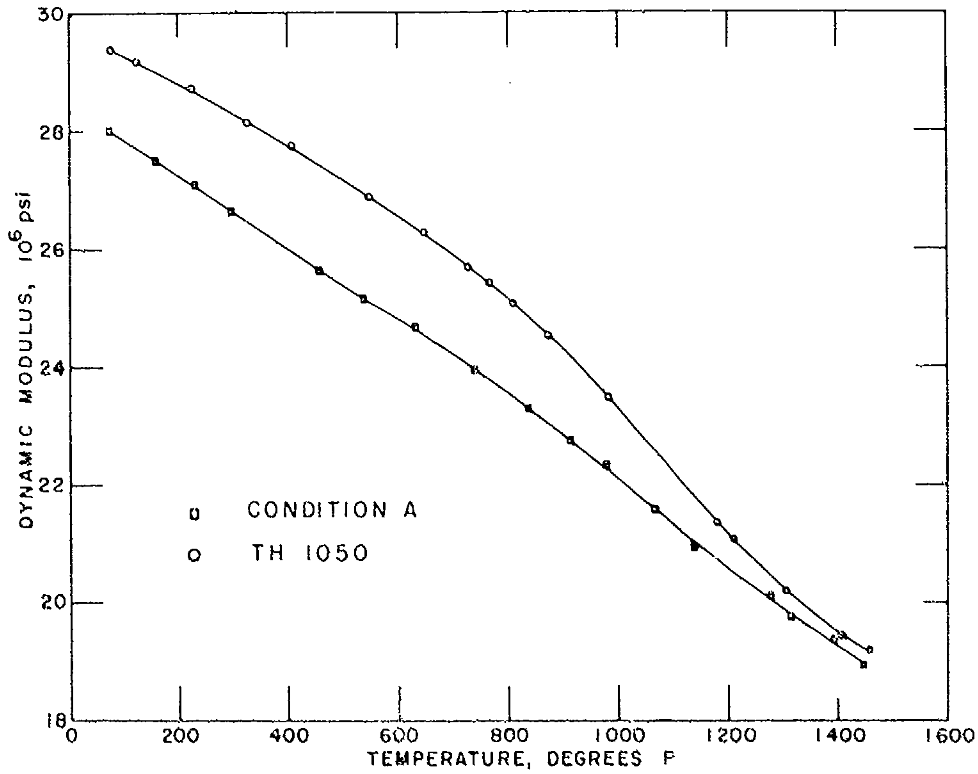

Figure 23. Dynamic Modulus as a Function of Temperature for PH 15 - 7 Mo (Conditions A and TH 1050)

A-286

Composition:

	Actual, %	Limits, % (Ref. 15)
Carbon	0.091	0.08 max
Manganese	0.98	1.00-2.00
Phosphorus	0.021	0.040 max
Sulfur	0.006	0.030 max
Silicon	0.625	0.40-1.00
Chromium	15.47	13.50-16.00
Nickel	25.93	24.00-27.00
Molybdenum	1.14	1.00-1.50
Titanium	2.30	1.90-2.30
Aluminum	0.30	0.35 max
Vanadium	0.29	0.10-0.50
Iron	Balance	Balance

Heat Treatment:

Solution H.T. 1800 F, 1 hour, water quenched, Precipitation hardened 1350 F, 18 hours, air cooled.

Specific Gravity: 7.903

Room Temperature Modulus:

Static: 28.8×10^6 psi (Heat Treated)
Dynamic: 28.42×10^6 psi (Heat Treated)

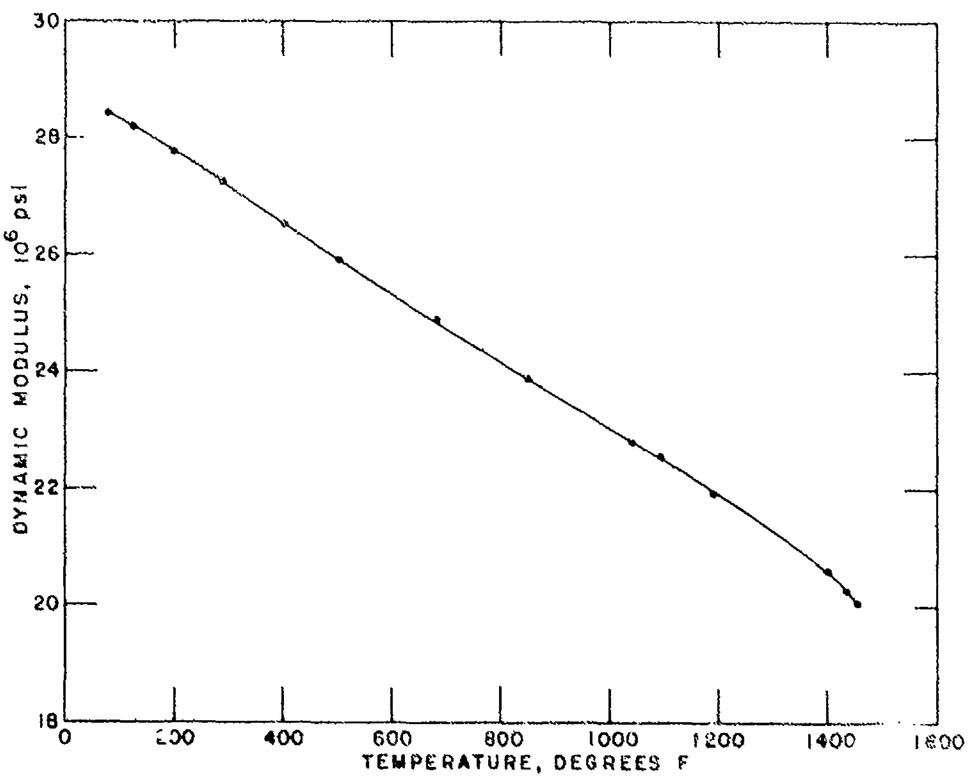

Figure 24. Dynamic Modulus as a Function of Temperature for A-286 (Heat Treated)

INVAR

Composition:

	Actual, %	Nominal, %
Nickel	35.60	36
Iron	Balance	Balance

Density: 0.2925 lb/in^3

Discussion:

As a result of its ferromagnetism this material exhibited a linear positive temperature coefficient of modulus of 0.0047×10^6 psi per degree F (Average of 2 samples) in the temperature range, room temperature to 400 F.

Room Temperature Dynamic Modulus:

Sample No. 1: 21.74×10^6 psi
Sample No. 2: 21.65×10^6 psi

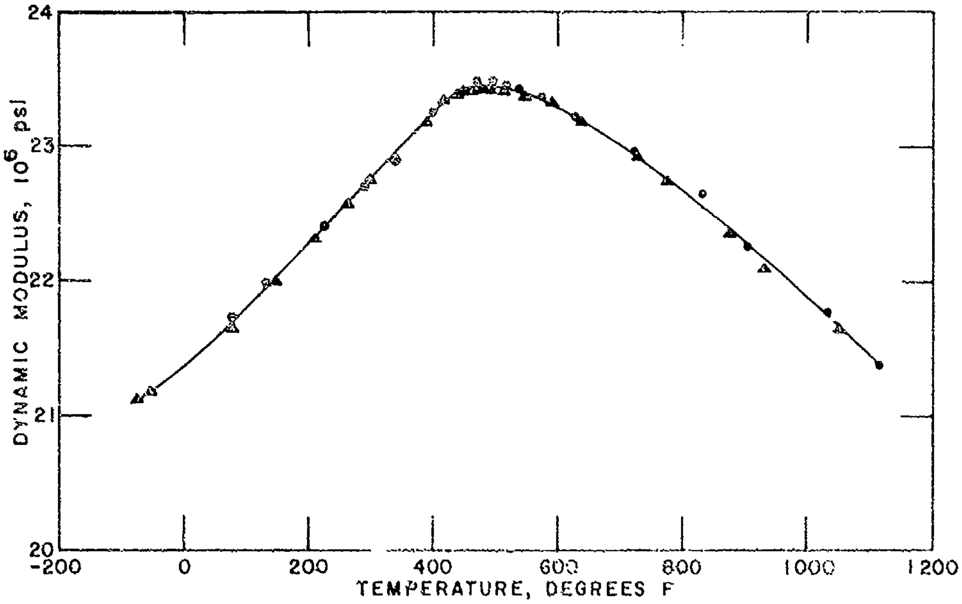

Figure 25. Dynamic Modulus as a Function of Temperature for Invar (2 Samples)

S - 816

Composition:

	Actual, %	Limits, % (Ref. 16)
Carbon	0.358	0.32-0.42
Manganese	1.39	1.00-2.00
Silicon	0.38	1.00 max
Chromium	19.92	19.00-21.00
Nickel	19.94	19.00-21.00
Molybdenum	3.86	3.50-4.50
Tungsten	4.90	3.50-4.50
Columbium (Nb)	2.87	3.50-4.50
Iron	3.85	5.00 max
Cobalt	43.40	40.00 min

Heat Treatment:

Heat Treated - the bar stock was received in a heat treated condition but the exact conditions were not known. As-received hardness was R_c 35.

Re-Heat Treated - the bar stock was given the following heat treatment:

2150 F, 1 hour, water quenched
1400 F, 16 hours, air cooled

Hardness after re-heat treatment was R_c 23.

Specific Gravity: 8.601

Discussion:

A difference of about 0.75×10^6 psi exists between the dynamic moduli of this material in its two heat treatments for the temperature range investigated.

Room Temperature Modulus:

Static: 34.9×10^6 psi (Re-Heat Treated)
Dynamic: 33.85×10^6 psi (Re-Heat Treated)

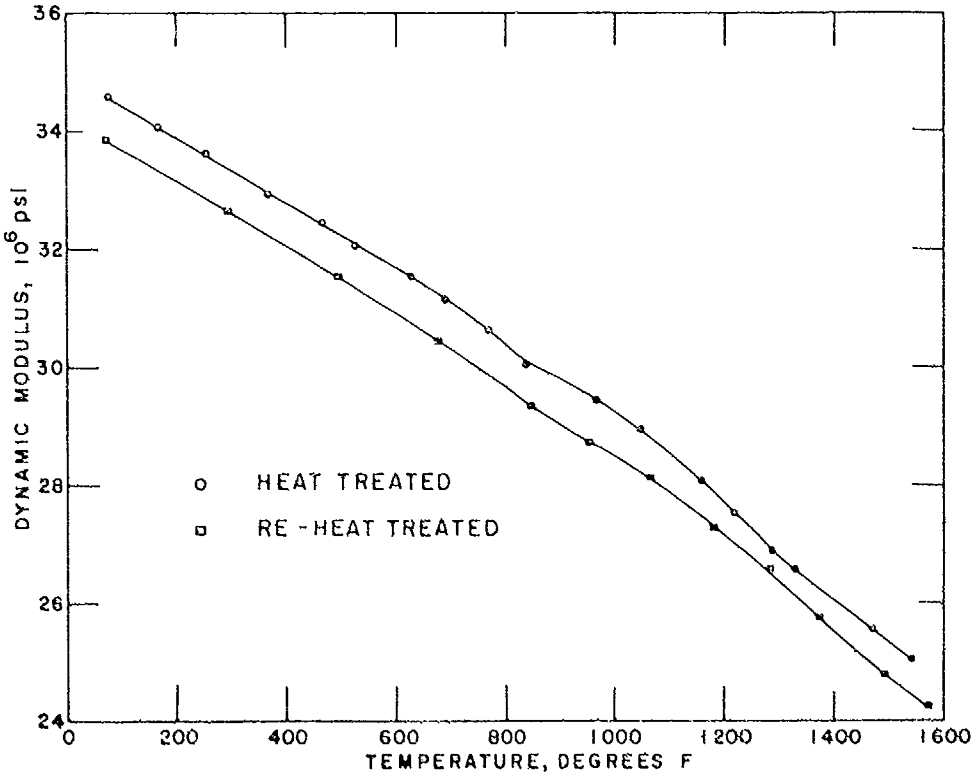

Figure 26. Dynamic Modulus as a Function of Temperature for S-816 (Two Heat Treatments)

ELECTROLYTIC NICKEL

Composition:

	Actual, %
Carbon	0.01
Manganese	<0.004
Silicon	0.01
Phosphorus	0.014
Sulfur	0.001
Nickel	Balance

Material Condition:
As-electrolytically-deposited

Specific Gravity: 8.911

Room Temperature Dynamic Modulus:
29.32×10^6 psi

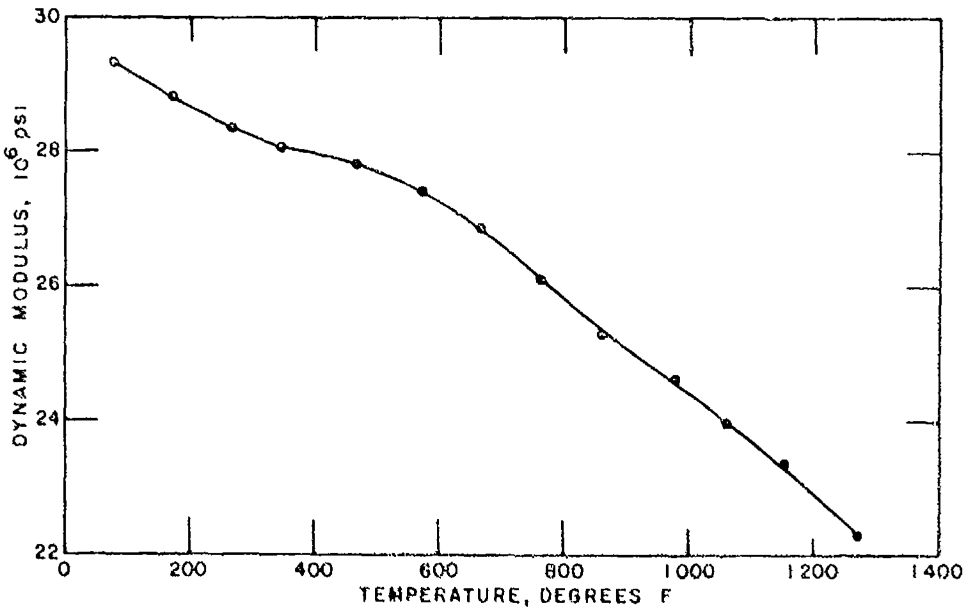

Figure 27. Dynamic Modulus as a Function of Temperature for Electrolytic Nickel (As Deposited)

INCONEL

Composition:

	Actual, %	Limits, % (Ref. 17)
Carbon	0.060	0.15 max
Manganese	0.25	1.0 max
Silicon	0.226	0.50 max
Chromium	13.65	12.0-15.0
Iron	6.97	9.0 max
Aluminum	0.06	—
Columbium (Nb)	<0.01	—
Titanium	<0.1	—
Nickel	Balance	75.0 % min

Material Condition:

Annealed, Hardness R_B 69

Specific Gravity: 8.474

Room Temperature Modulus:

Static: 31.6×10^6 psi

Dynamic: 31.43×10^6 psi

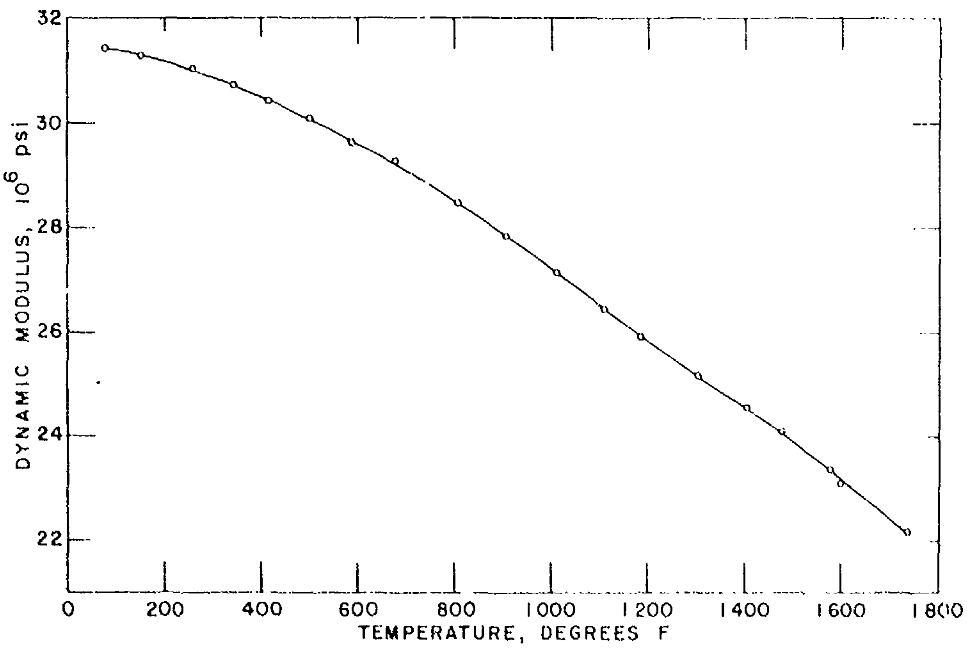

Figure 28. Dynamic Modulus as a Function of Temperature for Inconel (Annealed)

INCONEL W

Composition:

	Actual, %	Limits, % (Ref. 18)
Carbon	0.028	0.08 max
Manganese	0.50	1.00 max
Silicon	0.226	0.70 max
Chromium	15.95	14.00-17.00
Iron	6.30	5.00-9.00
Aluminum	0.50	0.40-1.00
Columbium (Nb)	<0.01	—
Titanium	2.40	2.00-2.75
Sulfur	—	0.01 max
Copper	—	0.50 max
Cobalt	—	1.0 max
Nickel	Balance	Balance

Material Condition:
Annealed, Hardness R_B 80

Specific Gravity: 8.247

Room Temperature Modulus:
Static: 31.0×10^6 psi
Dynamic: 30.71×10^6 psi

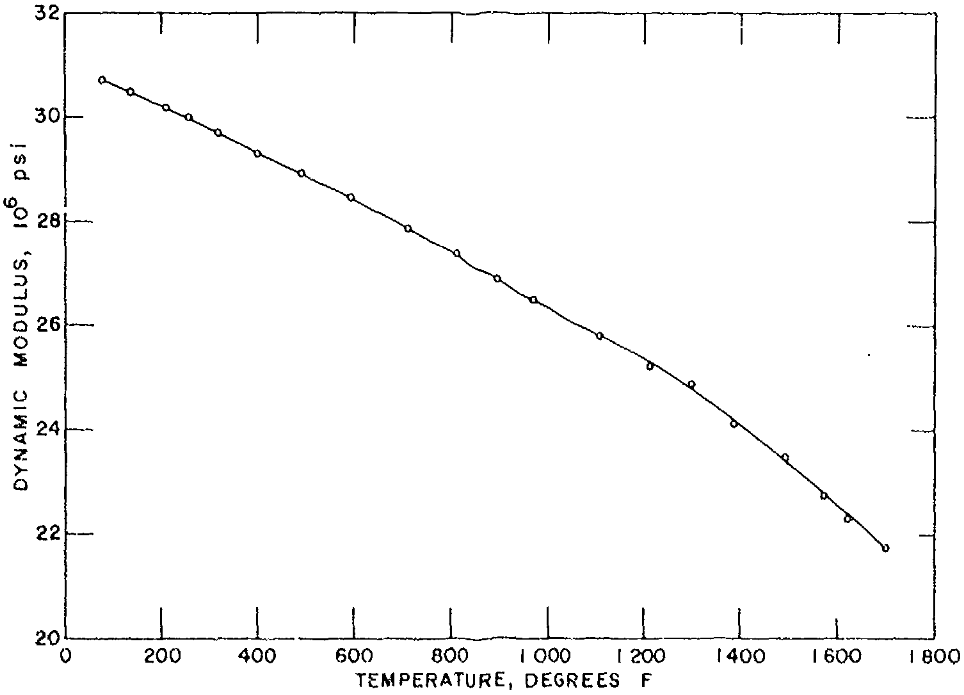

Figure 29. Dynamic Modulus as a Function of Temperature for Inconel W (Annealed)

INCONEL X

Composition:

	Actual, %	Limits, % (Ref. 19)
Carbon	0.060	0.08 max
Manganese	0.68	1.0 max
Silicon	0.30	0.50 max
Chromium	15.16	14.0-17.0
Iron	6.74	6.0-10.0
Aluminum	1.00	——
Columbium (Nb)	0.42	0.7-1.2
Titanium	2.55	2.25-2.75
Nickel	Balance	70.0 min

Heat Treatment:

2100 F, 3 hours, air cooled.
1500 F, 24 hours, air cooled.
1300 F, 20 hours, air cooled.

Specific Gravity: 8.216

Room Temperature Modulus:

Static: 31.6 x 10^6 psi (Heat Treated)
Dynamic: 31.51 x 10^6 psi (Heat Treated)

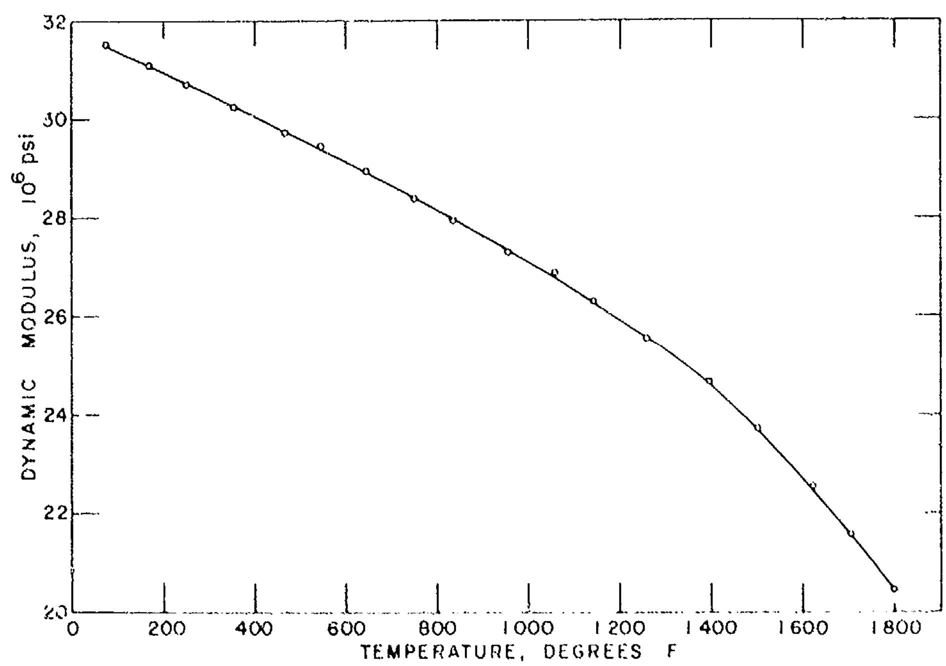

Figure 30. Dynamic Modulus as a Function of Temperature for Inconel X (Heat Treated)

HASTELLOY B

Composition:

	Actual, %	Limits, % (Ref. 20)
Carbon	0.046	0.05 max
Manganese	0.21	1.00 max
Silicon	0.15	1.00 max
Chromium	0.19	1.00 max
Molybdenum	29.10	26.00-30.00
Iron	6.54	4.00-7.00
Cobalt	——	2.50 max
Nickel	Balance	Balance

Heat Treatment:

2150 F, 45 minutes, air blast cooled.
1950 F, 2 hours, air blast cooled.
1500 F, 4 hours, air cooled.

Specific Gravity: 9.138

Room Temperature Modulus:

Static: 31.4×10^6 psi (Heat Treated)
Dynamic: 31.66×10^6 psi (Heat Treated)

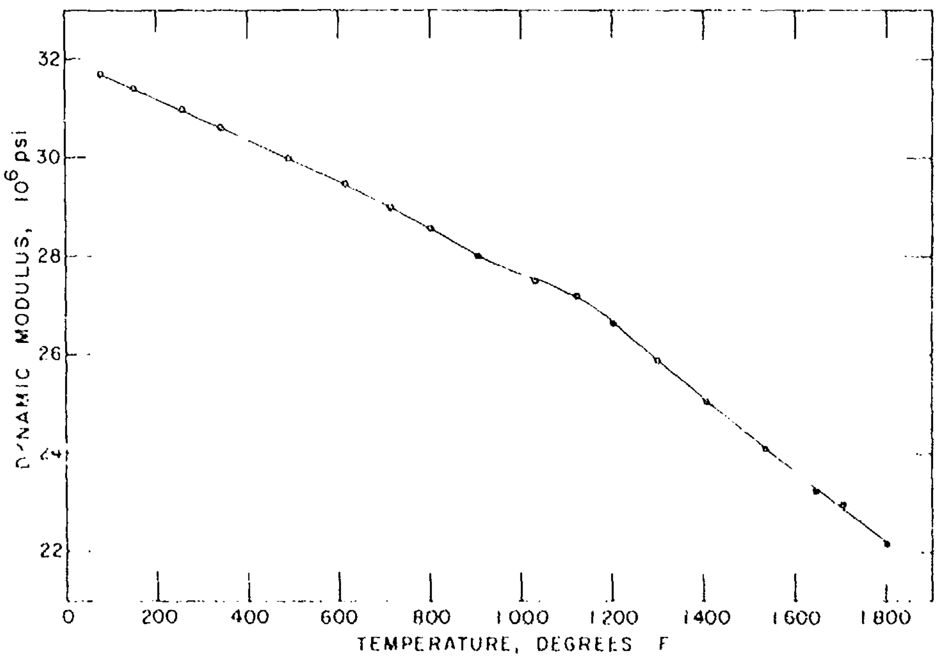

Figure 31. Dynamic Modulus as a Function of Temperature for Hastelloy B (Heat Treated)

NIMONIC 90

Composition:

	Actual, %	Limits, % (Ref. 21)
Carbon	0.033	0.1 max
Manganese	0.05	1.0 max
Silicon	0.39	1.5 max
Chromium	20.20	18-21
Cobalt	20.00	15-21
Molybdenum	<0.01	—
Aluminum	1.09	0.8-2.0
Iron	0.18	5.0 max
Titanium	2.48	1.8-3.0
Nickel	Balance	Balance

Heat Treatment:
1080 C (1975 F), 8 hours, air cooled
700 C (1292 F), 16 hours, air cooled

Specific Gravity: 8.161

Room Temperature Dynamic Modulus:
33.03 x 10^6 psi (Heat Treated)

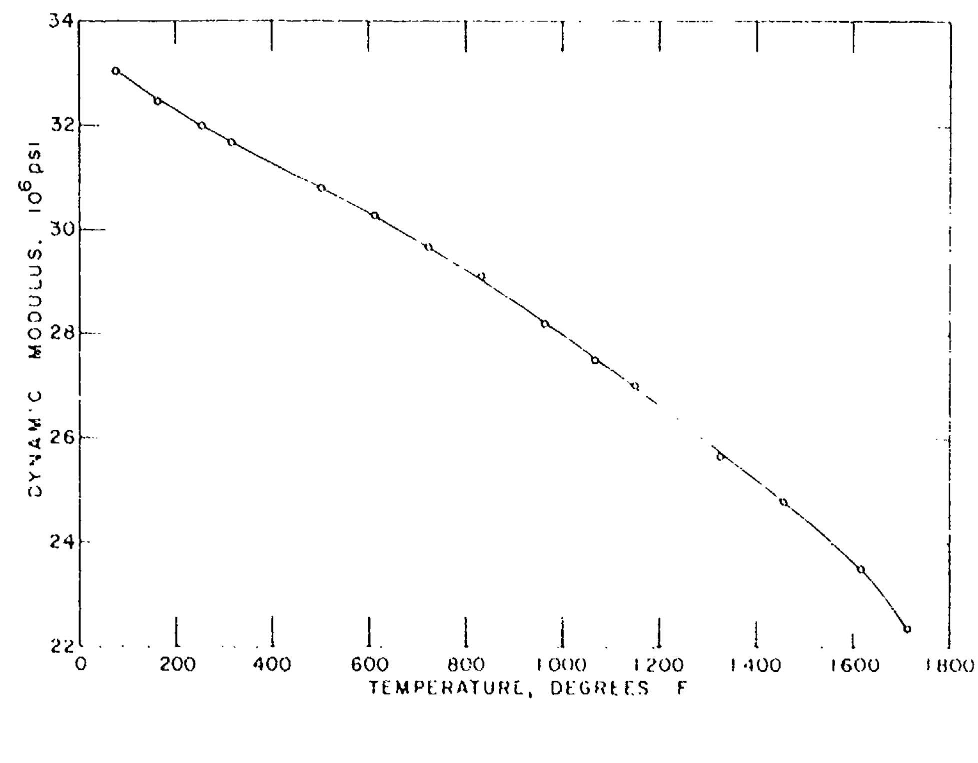

Figure 32. Dynamic Modulus as a Function of Temperature for Nimonic 90 (Heat Treated)

WASPALOY

Composition:

	Actual, %	Limits, % (Ref. 22)
Carbon	0.063	0.10 max
Manganese	0.02	0.50 max
Silicon	0.044	0.75 max
Chromium	20.28	18.00-21.00
Cobalt	13.35	12.00-15.00
Molybdenum	4.45	3.50-5.00
Aluminum	1.33	1.00-1.50
Iron	0.66	2.00 max
Titanium	2.84	2.75-3.25
Copper	<0.02	0.10 max
Zirconium	—	0.02-0.15
Boron	—	0.001-0.010
Nickel	Balance	Balance

Heat Treatment:

1975 F, 4 hours, air cooled.
1550 F, 4 hours, air cooled.
1400 F, 16 hours, air cooled.

Specific Gravity: 8.201

Room Temperature Modulus:

Static: 32.2×10^6 psi (Heat Treated)
Dynamic: 32.25×10^6 psi (Heat Treated)

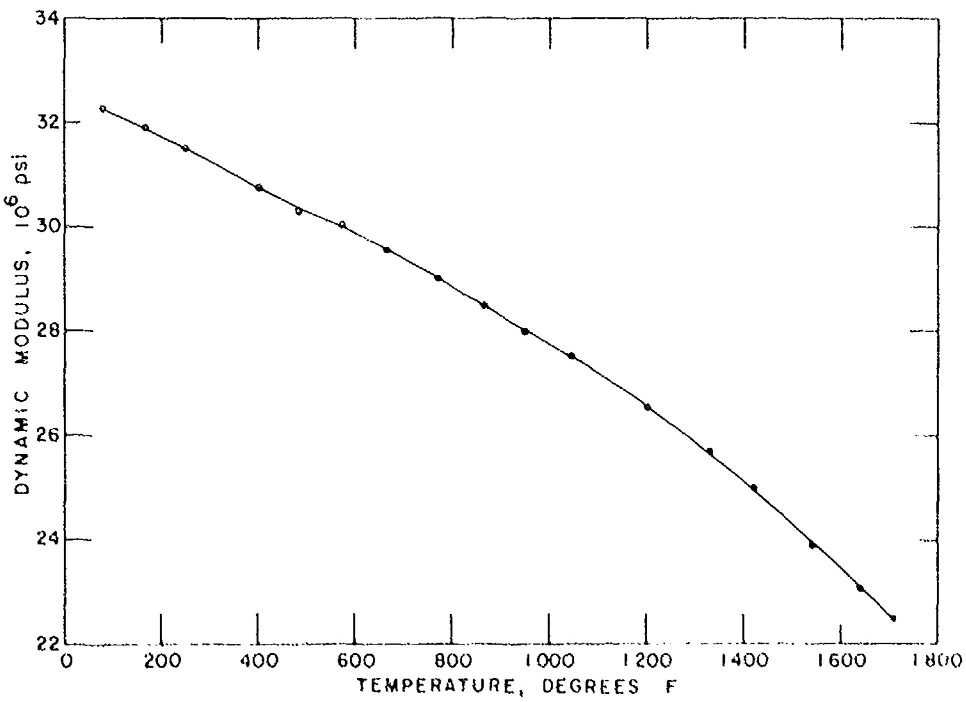

Figure 33. Dynamic Modulus as a Function of Temperature for Waspaloy (Heat Treated)

M 252

Composition:

	Actual, %	Limits, % (Ref. 23)
Carbon	0.144	0.10-0.20
Manganese	0.02	0.50-1.50
Silicon	0.056	0.30-1.00
Chromium	18.95	18.00-20.00
Cobalt	9.90	9.00-11.00
Molybdenum	10.04	9.00-11.00
Aluminum	0.90	0.75-1.25
Iron	0.75	5.00 max
Titanium	2.35	2.25-2.75
Nickel	Balance	Balance

Heat Treatment:

1900 F, 4 hours, air cooled.
1400 F, 15 hours, air cooled.

Specific Gravity: 8.073

Discussion:

The specific gravity of this material was found to be about 2 % lower than the 8.25 value reported by General Electric (Ref. 23) and may be a contributing factor for the dynamic modulus being lower than the static modulus.

Room Temperature Modulus:

Static: 30.2×10^6 psi (Heat Treated)
Dynamic: 29.07×10^6 psi (Heat Treated)

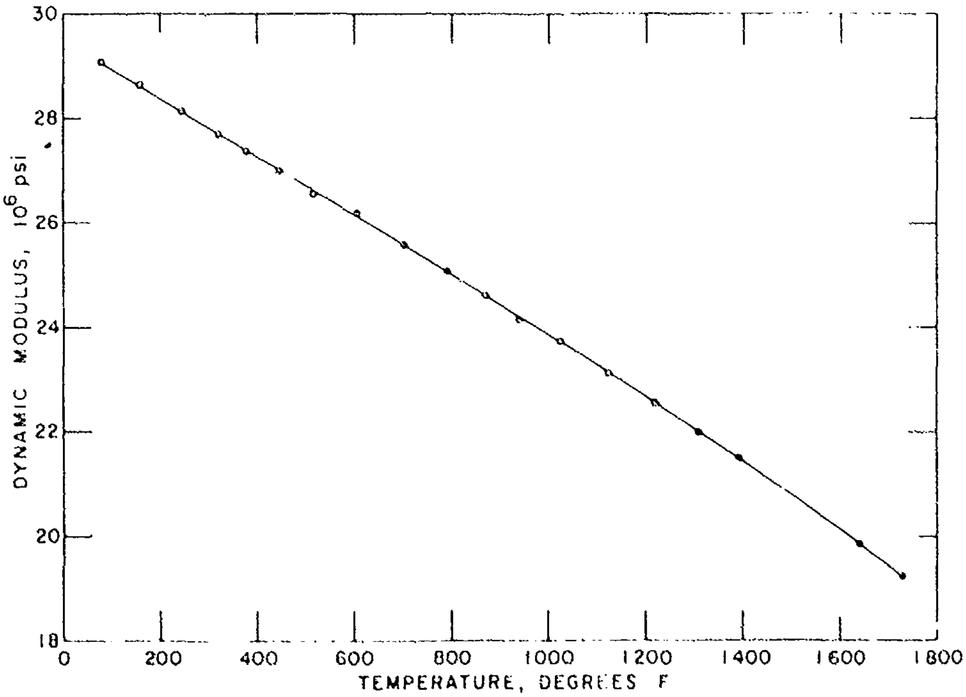

Figure 34. Dynamic Modulus as a Function of Temperature for M-252 (Heat Treated)

RENÉ 41

Composition:

	Actual, %	Limits, % (Ref. 24)
Carbon	0.09	0.06-0.12
Manganese	< 0.04	0.50 max
Silicon	0.10	0.50 max
Chromium	18.88	18.00-20.00
Cobalt	11.22	10.00-12.00
Molybdenum	9.79	9.00-10.50
Aluminum	1.63	1.50-1.80
Iron	< 0.30	5.00 max
Titanium	3.21	3.00-3.30
Boron	—	0.003 max
Nickel	Balance	Balance

Heat Treatment:
1950 F, 30 minutes, air cooled.
1400 F, 16 hours, air cooled.

Specific Gravity: 8.251

Room Temperature Modulus:
Static: 31.9×10^6 psi (Heat Treated)
Dynamic: 31.88×10^6 psi (Heat Treated)

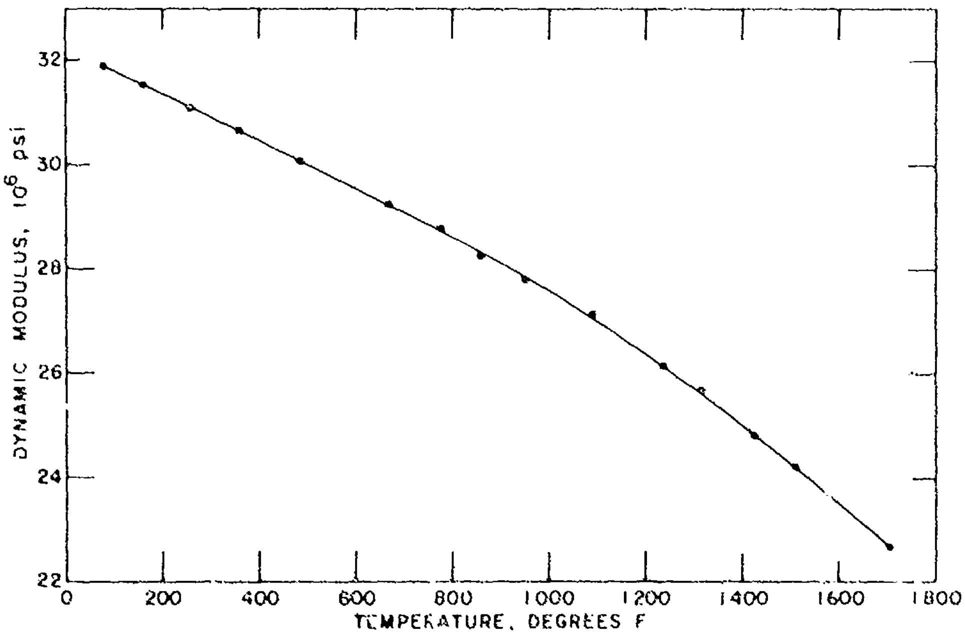

Figure 35. Dynamic Modulus as a Function of Temperature for René 41 (Heat Treated)

UDIMET 500

Composition:

	Actual, %	Limits, % (Ref. 25)
Carbon	0.093	0.15 max
Manganese	0.02	0.75 max
Silicon	0.044	0.75 max
Chromium	20.16	15.00-20.00
Cobalt	18.78	13.00-20.00
Molybdenum	4.05	3.00-5.00
Aluminum	2.65	2.50-3.25
Iron	0.64	4.00 max
Titanium	3.00	2.50-3.25
Copper	< 0.02	—
Sulfur	—	0.015 max
Boron	—	0.010 max
Nickel	Balance	Balance

Heat Treatment:

2150 F, 2 hours, air cooled.
1975 F, 4 hours, air cooled.
1550 F, 24 hours, air cooled.
1400 F, 16 hours air cooled.

Specific Gravity: 8.029

Room Temperature Modulus:

Static: 32.3×10^6 psi (Heat Treated)
Dynamic: 32.14×10^6 psi (Heat Treated)

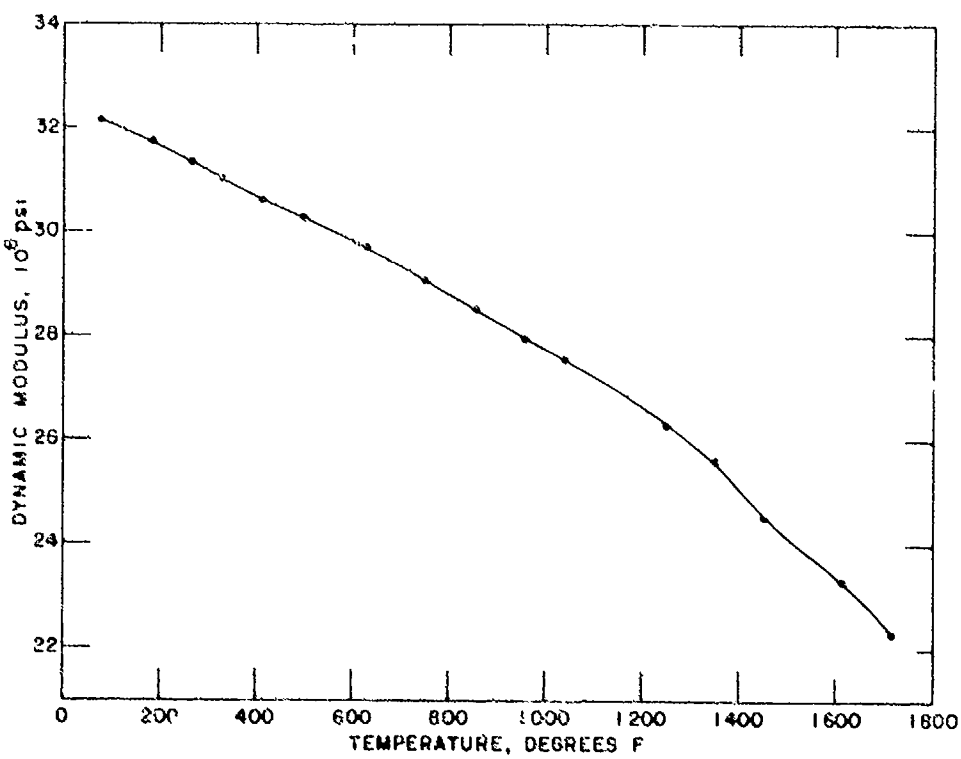

Figure 36. Dynamic Modulus as a Function of Temperature for Udimet 500 (Heat Treated)

UDIMET 700

Composition:

	Wrought		Cast	
	Actual, %	Limits, % (Ref. 26)	Actual, %	Limits, % (Ref. 26)
Carbon	0.07	0.15 max	0.05	0.1 max
Manganese	0.10	0.15 max	< 0.1	0.15 max
Sulfur	0.007	0.015 max	0.007	0.015 max
Silicon	0.10	0.2 max	0.02	0.2 max
Chromium	15.5	13-17	14.45	14-16
Molybdenum	5.00	4.5-5.5	5.00	4.5-5.5
Titanium	3.50	2.75-3.75	3.60	2.75-3.75
Aluminum	4.33	3.75-4.75	4.70	3.75-4.75
Iron	0.12	4.0 max	0.52	4.0 max
Cobalt	18.0	14-20	19.00	17-20
Copper	0.10	0.10 max	neg.	0.10 max
Zirconium	0.05	0.06 max	< 0.03	0.06 max
Boron	0.032	0.001-0.050	0.029	0.025-0.035
Nickel	Balance	Balance	Balance	Balance

Heat Treatment:

Wrought

2125 F, 2 hours, air cooled.
1975 F, 4 hours, air cooled.
1550 F, 24 hours, air cooled.
1400 F, 16 hours, air cooled.

Cast

2100 F, 2 hours, air cooled.
1400 F, 16 hours, air cooled.

Specific Gravity:

Wrought

7.933

Cast

1 - 7.931
2 - 7.919

Discussion:

The dynamic moduli of two samples of wrought material (heat treated) are shown to be in good agreement even though the heat treatment had been repeated on one of the samples. Shown also are the results of two samples of cast material (heat treated) which were supplied by the Aircraft Gas Turbine Division of General Electric Company. The samples were machined from cast turbine blades having the heat treatment shown above.

Room Temperature Modulus:

Wrought

Static: 32.4×10^6 psi (Heat Treated)
Dynamic 32.45×10^6 psi (Heat Treated)

Cast

Dynamic # 1 29.67×10^6 psi (Heat Treated)
Dynamic # 2 30.58×10^6 psi (Heat Treated)

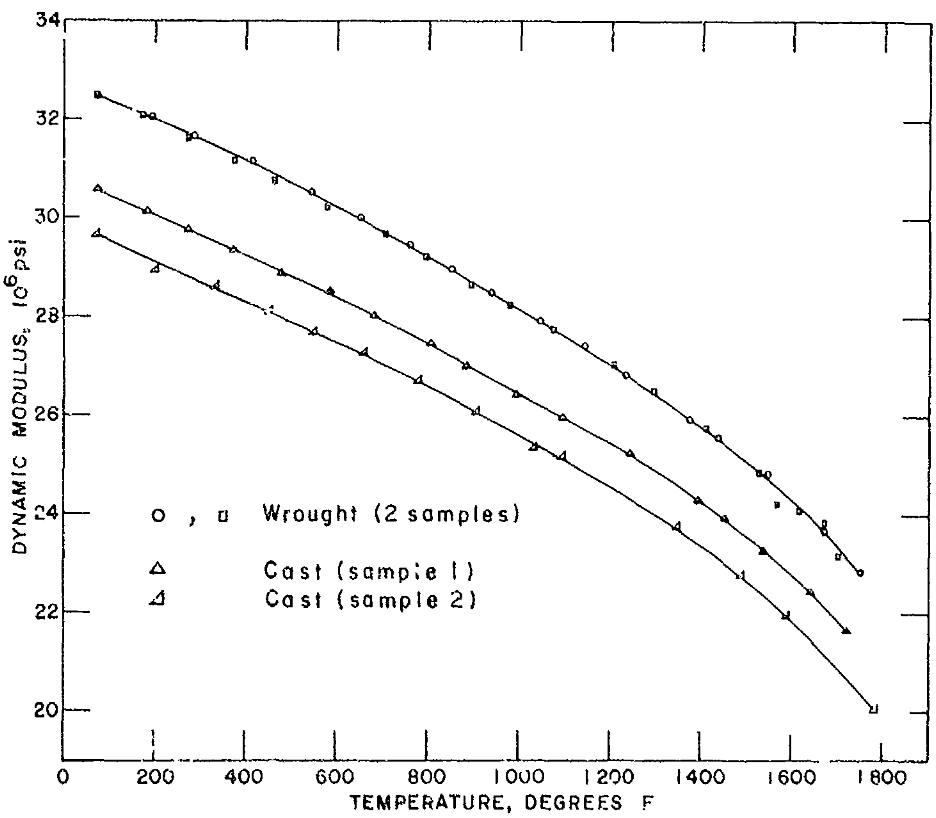

Figure 37. Dynamic Modulus as a Function of Temperature for Udimet 700 (Wrought and Cast, both Heat Treated)

INCONEL 700

Composition:

	Actual, %	Limits, % (Ref. 27)
Carbon	0.135	0.16 max
Manganese	0.25	2.0 max
Silicon	0.018	1.0 max
Chromium	15.35	13.0-17.0
Cobalt	28.98	24.00-34.00
Molybdenum	3.09	1.0-4.50
Aluminum	3.29	2.50-3.50
Iron	0.25	4.00 max
Titanium	2.28	1.75-2.75
Sulfur	—	0.015 max
Copper	—	0.5 max
Nickel	Balance	Balance

Heat Treatment:
2160 F, 2 hours, air cooled.
1600 F, 4 hours, air cooled.

Specific Gravity: 8.076

Room Temperature Modulus:
Static: 32.1×10^6 psi (Heat Treated)
Dynamic: 32.56×10^6 psi (Heat Treated)

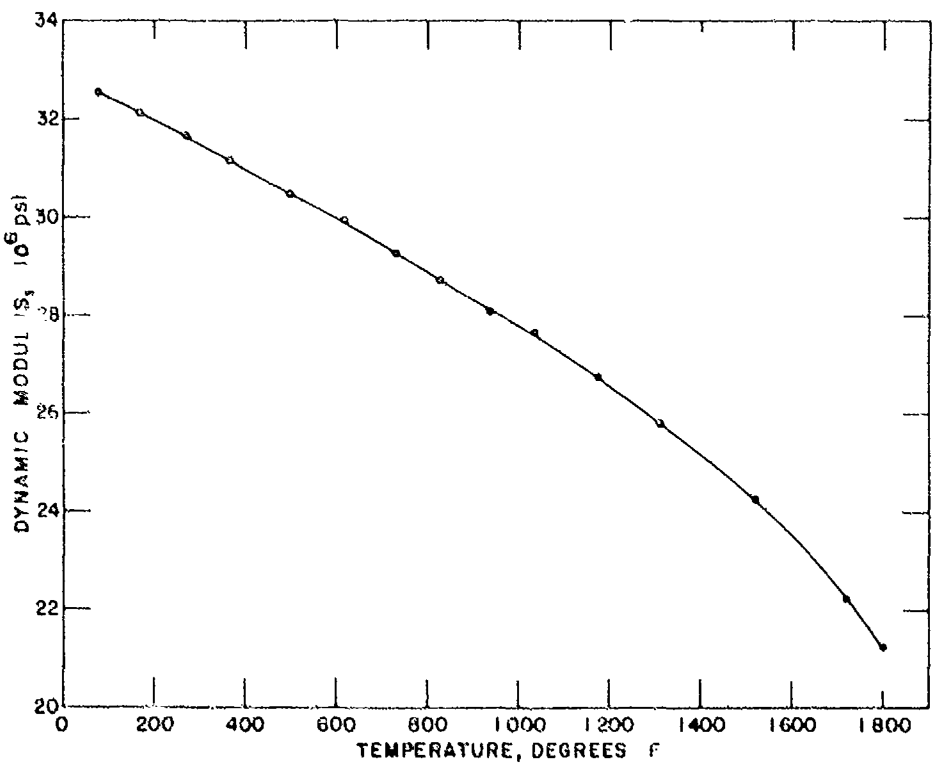

Figure 38. Dynamic Modulus as a Function of Temperature for Inconel 700 (Heat Treated)

INCONEL 713C

Composition:

	Actual, %	Limits, % (Ref. 28)
Carbon	—	0.20 max
Manganese	—	1.0 max
Sulfur	—	0.015 max
Silicon	—	1.0
Chromium	11.9	11.0-14.0
Molybdenum	5.0	3.5-5.5
Titanium	0.52	0.25-1.25
Aluminum	5.6	5.5-6.5
Iron	—	5.0 max
Columbium (Nb)	2.1	1.0-3.0
Tantalum	—	1.0-3.0
Nickel	Balance	Balance

Material Condition:

Specimens machined from investment cast tensile specimen blanks and tested in the as-investment-cost condition.

Specific Gravity: 7.905

Room Temperature Dynamic Modulus:

30.27×10^6 psi

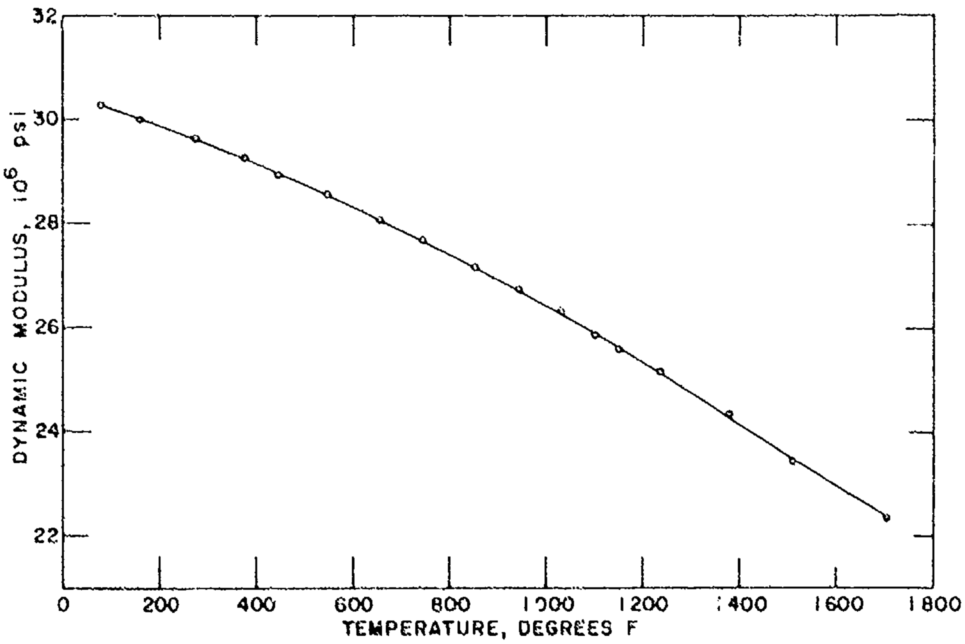

Figure 39. Dynamic Modulus as a Function of Temperature for Inconel 713 C (As Investment Cast)

COMMERCIAL PURITY MOLYBDENUM

Composition:

	Actual
Carbon	0.2 %
Hydrogen	1 ppm
Nitrogen	3 ppm
Oxygen	14 ppm
Molybdenum	Balance

Specific Gravity: 10.212

Discussion:

The sample was tested in a closed furnace flushed with helium. The static modulus value reported was taken from an autographic stress-strain plot made with an SR-4 clip-on extensometer.

Room Temperature Modulus

Static: 47.2×10^6 psi

Dynamic 46.35×10^6 psi

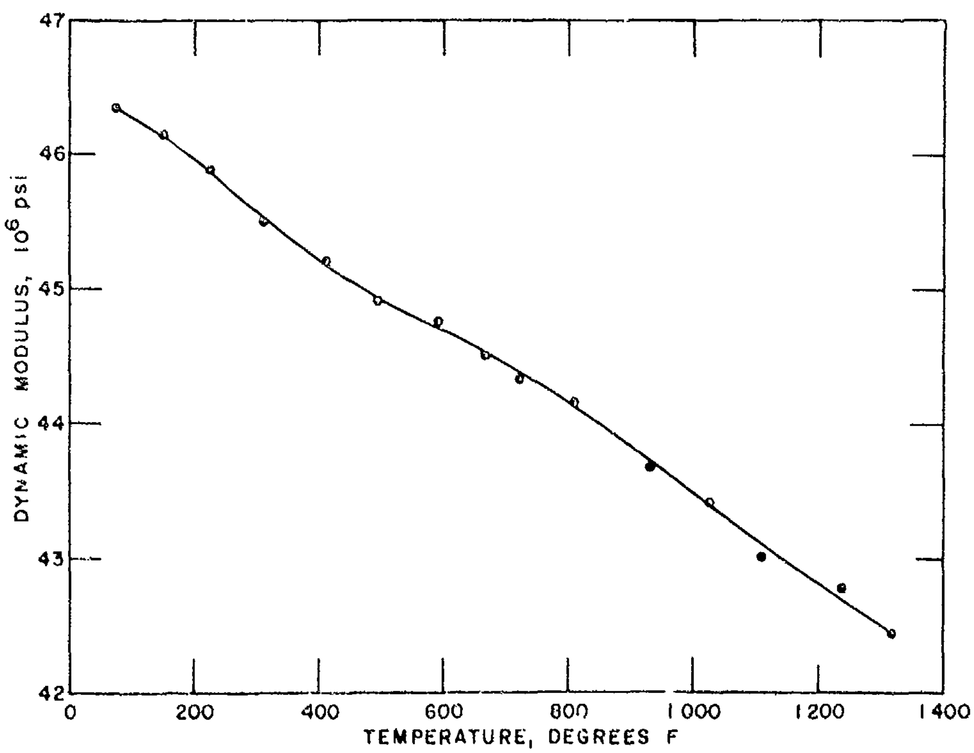

Figure 40. Dynamic Modulus as a Function of Temperature for Commercial Purity Molybdenum

VANADIUM

Composition:

	Aluminothermic	Calcium-Reduced
Carbon	0.025	0.05
Oxygen	0.035	0.086
Hydrogen	0.0023	0.0032
Nitrogen	0.0058	0.056
Vanadium	Balance	Balance

Material Condition:

Aluminothermic: recrystallized (see WADD TR 60-245, Ref. 8, for specimen preparation details)

Calcium-Reduced: cold-worked rod.

Density:

Aluminothermic 0.221 lb/in^3

Calcium Reduced 0.221 lb/in^3

Discussion:

Only a slight difference in the moduli of aluminothermic vanadium and calcium-reduced vanadium was found over the temperature range studied, even though the materials had two markedly different structures. The calcium-reduced vanadium had a cold-worked structure whereas the aluminothermic vanadium was recrystallized.

Both materials were tested in a closed furnace flushed with helium.

Room Temperature Dynamic Modulus:

Aluminothermic 18.70 x 10^6 psi

Calcium-Reduced 18.60 x 10^6 psi

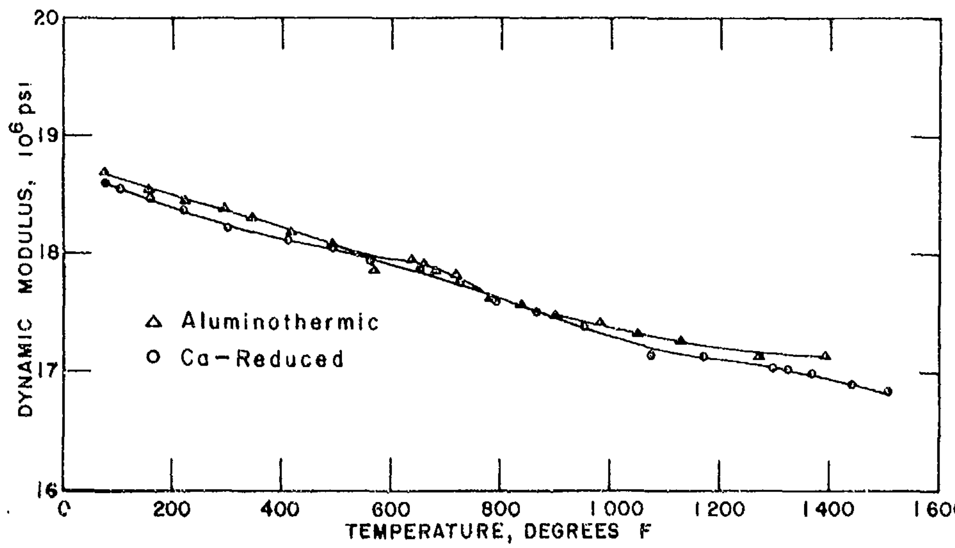

Figure 41. Dynamic Modulus as a Function of Temperature for Vanadium (Aluminothermic and Calcium-Reduced)

COMMERCIAL PURITY TUNGSTEN

Composition

	Actual
Carbon	0.03 %
Hydrogen	1 ppm
Nitrogen	< 1 ppm
Oxygen	99 ppm
Tungsten	Balance

Specific Gravity: 19.154

Discussion:

The tungsten sample was tested in a closed furnace flushed with helium.

Room Temperature Dynamic Modulus:

58.56×10^6 psi

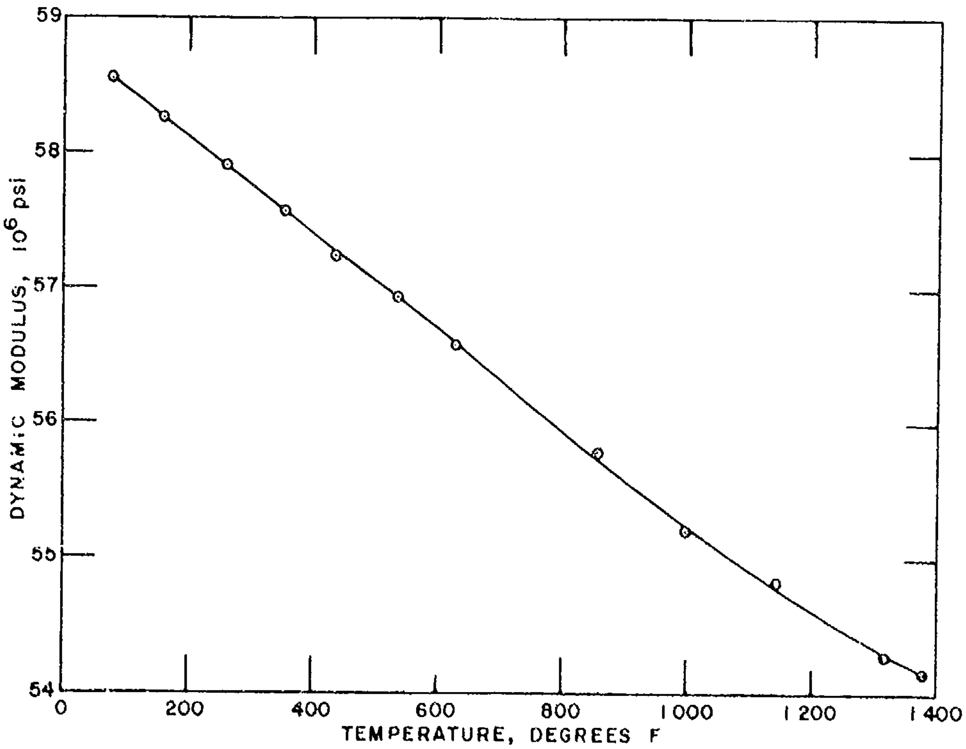

Figure 42. Dynamic Modulus as a Function of Temperature for Commercial Purity Tungsten

F - 80

Composition:

	Actual	Nominal % (Ref. 29)
Carbon	0.03 %	0.03-0.08
Oxygen	154 ppm	0.04 max
Nitrogen	26 ppm	0.03 max
Hydrogen	9 ppm	—
Tantalum	0.071 %	0.10 max
Zirconium	1.17 %	0.80-1.20
Columbium (Nb)	Balance	Balance

Material Condition:

As-cold-drawn to 1/4 inch rod.

Specific Gravity: 8.556

Discussion:

Although these tests were performed in a small closed furnace flushed with 15 cubic feet per hour of helium, considerable oxidation of the F-80 samples occurred. The samples were heated and cooled in helium, with the total time at temperatures above 800 F being about 2 hours. Room temperature dynamic modulus determinations were made after cooling to assess the modulus changes attributable to oxidation. Both samples exhibited a room temperature modulus increase of 0.37 x 10^6 psi. A Knoop microhardness traverse was performed using a 100 gram load. Hardness varied from KHN 454 (Rc 44 using steel conversion tables) near the surface to KHN 134 (R_B 67 using steel conversion tables) at the center of the 1/4 inch diameter specimen. Oxide thickness was measured on the sample which was polished for microhardness tests. The oxide layer averaged 0.00037 inches in thickness.

Room Temperature Dynamic Modulus (prior to heating)

Sample No. 1 15.14 x 10^6 psi

Sample No. 2 15.08 x 10^6 psi

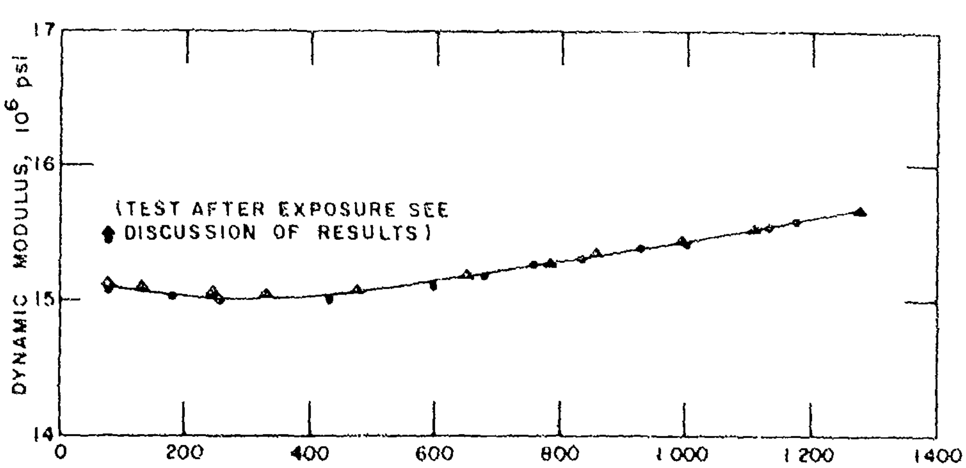

Figure 43. Dynamic Modulus as a Function of Temperature for F-80 (As Cold Drawn, 2 Samples)

DISCUSSION OF RESULTS

The preceding data sheets present in a graphic manner the results of dynamic modulus determinations for a wide spectrum of metals and alloys.

The modulus of the typical material exhibits a negative temperature coefficient that changes with temperature. When the temperature is increased the coefficient increases in the negative direction, i.e., the modulus-temperature curve is concave downward.

Several materials produce a nearly linear decrease in modulus with temperature, i.e. the modulus has a constant temperature coefficient. Examples of such materials are high-purity aluminum, 7075-T6, Ti-6A1-4V, M 252 and commercial purity tungsten.

Changing the structure of a material may produce a change in modulus. This can be seen in several of the plots comparing heat treated and annealed alloys. The material with the heat-treated structure may have a higher or lower modulus than the same material when annealed. For example, the modulus of PH 15-7Mo (Figure 22) is increased by heat treatment whereas the converse is true for La Belle HT (Figure 16). Thus, it is reasonable to assume that prominent changes in slope of the modulus-temperature plot indicate the initiation of a structural change within the material. The irregularities thus produced in the modulus-temperature plot are not as abrupt as they would be if the specimen and apparatus were soaked at each temperature for a substantial length of time. Since the tests were performed with a gradually increasing temperature, structural changes due to precipitation hardening, tempering, etc., are not carried to completion until a much higher temperature has been reached. The modulus values with minimum time at temperature are considered to be more important for short time exposure properties which are needed in missile applications. Also, precipitation hardening materials and tempered steels are not commonly used above their hardening temperatures for continued lengths of time.

Invar exhibited the unique characteristic of a linear positive slope in the modulus-temperature plot (Figure 25). For temperatures up to 400°F the modulus of Invar increases 0.0047×10^6 psi per degree F because of its magnetic properties. At lower temperatures Invar has strong ferromagnetism which disappears beginning at 325°F for annealed Invar and 400°F for quenched Invar (Ref. 30).

For iodide titanium, Ti-75A, molybdenum, vanadium, tungsten and F-80 an inert atmosphere was required. For this purpose the closed chamber within the furnace was flushed with 10 to 20 cubic feet of helium per hour. This method proved to be quite effective for most materials. The system was sufficiently oxygen-free to prevent formation of the V_2O_5 vanadium oxide up to 1500°F. V_2O_5 is easily detected, since it is a liquid phase at temperatures above 675°C (1247°F) (Ref. 31).

The inert atmosphere, although effective on other materials, was not sufficiently oxygen-free to prevent severe oxidation of the cold worked F-80 (columbium - 0.7 zirconium). The modulus of F-80 had a normal negative temperature coefficient up to 300°F where it decreased to zero and became positive from 500°F on up. A duplicate specimen exhibited the same behavior. Room temperature modulus was redetermined after testing and was 0.37×10^6 psi higher for both samples. A Knoop micro-hardness traverse revealed a variation in hardness of KHN 454 near the surface to KHN 134 at the center. The oxide layer was measured optically and found to average 0.00037 inches

in thichness. Since the F-80 stock was cold drawn to 1/4-inch rod one might suspect that exposure to the test temperature would initiate recrystallization, resulting in a change in mechanical properties. However the data of Page (Ref. 32) show the temperature for initiation of recrystallization of Columbium with similar composition and cold work to be 960°C (1760°F) for a 1-hour exposure. Maximum exposure conditions during testing were 1 hour at 1400°F. Thus it is concluded that the positive temperature coefficient of F-80 above 500°F and the increased room temperature modulus after testing were results of oxidation and that change of material structure had a negligible effect.

CONCLUSIONS

This investigation demonstrated that the elastic moduli of metals may be determined dynamically at elevated temperatures by using longitudinal resonance as the basic parameter. This method was employed in establishing the elevated temperature dynamic moduli of 40 metals and alloys reported herein. A room temperature comparison of dynamic and static moduli has been presented for most of the materials investigated.

This simple and straight forward method of determining dynamic modulus requires only one specimen for a complete modulus-temperature plot. It has provided reproducible data which indicate the structural changes taking place in a material.

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